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A set of coaxial sample holders together with a measurement and data reduction technique has been developed and applied to the study of the dielectric properties ($\varepsilon^*=\varepsilon'-j\varepsilon''$) of wheat, corn, and soya over the 1 to 200 MHz range. Particular attention was given to the behavior of the dielectric properties as a function of percent moisture content, frequency, and packing density. Data were also taken to evaluate the dependence of dielectric properties on temperature and sample holder configuration. Some study was also devoted to the correlation between dielectric constant (ε'), loss factor (ε''), loss tangent ($\varepsilon''/\varepsilon'$), and percent moisture content. Particular emphasis was devoted to a study of high moisture corn (up to 40%).

Key words: Dielectric properties; grain; loss tangent; moisture.

1. INTRODUCTION AND BACKGROUND

One of the most important parameters in the handling, storing, marketing, and use of grain is the moisture content. At every phase, including seeding and harvest, through marketing and transport to its final use as human and animal food, the moisture content needs to be repeatedly and accurately monitored. There are many methods available for measuring moisture content. In reference [1]* is a compilation of ten methods, together with the advantages and disadvantages of each. Even if the same grain sample were tested by each method and the measurement procedure were carried out perfectly, it is probable that there would be a range of disagreement among the results. This is caused by the fact that the various methods do not measure precisely the same phenomena and that the moisture characteristics are sometimes altered by the measurement processes. There is general agreement that moisture in grain is present in several forms, and complete understanding of the processes of moisture gain and moisture loss is lacking [1]. Thus, the measurement of moisture content is sometimes difficult, and no single ideal method has been developed. Furthermore, there is considerable disagreement as to which methods should be used for a specific purpose, and a variety of methods and instruments are in use in the United States and throughout the world.

Present methods of grain moisture measurement are unsatisfactory because they are inaccurate, inconvenient, or slow. A desirable method would be a quick one capable of achieving accuracies of ± 0.5 percent or better without the necessity for special preparation of the grain.

1.1 U.S.D.A. Approved Method

A system widely used in the United States and the one adopted by the U.S. Department of Agriculture utilizes an electric capacitance type of moisture meter which is referred, through a series of calibration charts, to specific grain samples whose percentage moisture content has been determined by the oven-dry method [2]. The electric meters are used because they provide a rapid method of measurement that is easily adapted to field use. In essence, the electrical method uses a capacitance cell to provide an indication of percent moisture content based upon the dielectric constant of grain. The electric meter reading, which is some function of the dielectric constant, is converted to moisture content by means of U.S.D.A. calibration charts.

*Figures in brackets indicate the literature references at the end of this paper.

1.2 Dielectric Parameters as Related to Moisture Content

It should be clear that the present work is a straight-forward measurement of dielectric constant and loss versus moisture content. The packing density of the grain samples was measured at the same time as the dielectric constant. A literature search did not reveal a previous extensive effort of this type.

Most commercial electrical moisture meters give a reading approximately proportional to dielectric constant with some allowance for density. This reading may be combined with calibration tables (or more correctly, correlation tables) which convert the reading into a percentage moisture content. This being so, tables can also be made that convert the fundamental physical quantities, dielectric constant and/or loss, into moisture content. The present research is a start in examining the usefulness of absolute dielectric measurements *per se* for agricultural moisture measurements.

2. SOURCES OF VARIATION IN MOISTURE MEASUREMENT

Some of the difficulty in achieving accurate measurements of moisture content is attributable to the grain itself and therefore is not controllable by the measurement method. Included in this category is the fact that moisture content is not a stable condition, but one which will vary with other conditions, such as temperature and humidity. There is evidence that different hybrid types of grain may give varying results both on the electric meters and by the oven-dry process, and it is well known that grain samples from the same stand taken at the same time will show variations in moisture content. Thus the complexity of an unstable material is added to the variations existing between different measurement methods.

3. SOURCES OF ERROR IN CAPACITANCE METHODS

When relying on the capacitance method to measure percent moisture content, several sources of error are encountered. They are mentioned here because the work to be described is directed toward their evaluation and possible elimination or reduction.

3.1 Correlation of Percent Moisture Content with Dielectric Constant

The principle of capacitance-type meters is predicated on the assumption that dielectric constant is a reliable indicator of moisture content. This assumption is generally correct, but other factors such as packing density, temperature, and measurement frequency affect the relationship. This report will provide data resulting from experiments designed to study the influence of these parameters. In addition to the influencing factors considered here, there are probably others such as protein and starch content, hybrid variety, growing conditions and others; however, they are not included in the work described.

3.2 The Effect of Other Parameters on Dielectric Constant

The scope of the work described in this report includes experiments which show the effect of several other parameters upon the observed dielectric constant of various grain samples. These other parameters include measurement frequency, density of the grain being measured, temperature, sample holder configuration, and overburden.

3.3 Difficulty in Measuring the Dielectric Constant of Particulate Material

The measurement of a homogeneous material, such as a liquid or a solid, is relatively simple compared to the problems encountered in measuring the dielectric constant of an inhomogeneous sample. In measuring the dielectric constant of grain we are dealing with a mixture of grain and air with the proportions of these two constituents being unknown. As this proportion changes, the observed dielectric constant will also change. This is not only true for a grain and air mixture, but it is true for any other mixture, such as air and glass beads or for a liquid-solid mixture. This is a serious problem which is detrimental to any dielectric measurement approach and one which will impose a limit on the (attainable) accuracy. This problem is of course related to the variation of dielectric constant with density as mentioned in section 3.2 above, but is probably more complex when the solid matter is itself inhomogeneous as is the case with grain or other organic materials.

4. SCOPE

The work described in this report has been done by the Electromagnetic Fields Division of the National Bureau of Standards in cooperation with the Grain Standardization Laboratory of the U.S. Department of Agriculture in Beltsville, Maryland. The thrust of the work has been the study of the dielectric properties of grain as a function of several variables including moisture content, frequency, and temperature. Because the electric capacitance type of moisture meter is a fast, inexpensive and convenient means for percent moisture content determination and because it is widely used, it is desirable to study the factors which contribute to measurement inaccuracy in the hope of bringing about improvement. Of particular concern is the measurement of high moisture corn above about 26 percent. This is brought about by changes in farming methods and the use of pickersheller equipment to harvest the grain in the very early stages of maturity when moisture percentages are large.

A clear cut solution to the moisture measurement problem was not the expected result of this work; indeed, that would be far too ambitious. But, recognizing the need for a data base which will provide quantitative information related to the problem of measuring the moisture content of grain by electrical or electromagnetic methods, we have developed measurement techniques and accumulated a quantity of data which may prove to be of value as work continues. Presented here are only some initial findings, and it is recognized that there is more to be done and improvements which could be made.

The data presented is for wheat, corn, and soya over the frequency range from 1 to 200 MHz, and the specific parameter investigated was the apparent or measured complex dielectric constant as a function of several influencing parameters including frequency, percentage moisture content, packing density, and temperature. Capacitance variation with sample holder configuration is also examined briefly. An attempt has been made to correlate percent moisture content with dielectric characteristics, and it is apparent that this relationship is affected by several other variables. Data are needed to show quantitatively what effect the other variables have. This work is a beginning in the development of such a data base.

5. TECHNIQUE AND APPARATUS

Three coaxial sample holders were constructed for use in the study of grain as well as other materials; one each for 5.04 cm(2"), 7.62 cm(3"), and 10.16 cm(4") diameters of the outer cylinder. To provide adequate space for large kernel grains, the sample holding portions of the holders have a 75 ohm characteristic impedance (see table 1) instead of the usual 50 ohms where the space between center and outer electrodes would have been smaller. Figure 1 is a photograph of the 10.16 cm (4") holder along with a sample dropping mechanism and a depth gauge for measuring the depth to which the holder was filled with grain. Construction details of the sample holders are shown in figure 2.

At low frequencies (less than 1 MHz) where an electrostatic approximation is adequate, the sample holder may be regarded as a coaxial capacitor with capacitive sections 1 through 4 (see figure 2) connected in parallel. In addition, changes in diameter of the tubing and/or the center conductor must be represented by shunt capacitors at the changes [3]. At higher frequencies the holder must be treated as a coaxial transmission line terminating in an open circuit. The exact location of the open circuit is somewhat beyond the end of the center conductor [3,4] as indicated in figure 2. Alternatively, a shunt capacitor may be used exactly at the end of the center conductor. We used the former representation.

The open circuited holder is convenient because inserting the sample consists simply in pouring the sample into the open end. Also, such a holder works at any low frequency and at higher frequencies if the criterion of equation (12) is obeyed. The sample space, section 1 in figure 2, extends beyond the end of the center conductor, as will be discussed.

Table 1. Sample holder characteristics

Holder Diameter	Overall Length	Z_o^* of Grain Sample Section	Length of outer Tube, Section 1.	Center Conductor Length (Section 1)
5.08 cm(2")	17.0 cm(6.68")	75 ohms	13.3 cm(5.25")	8.176 cm(3.219")
7.62 cm(3")	16.8 cm(6.60")	75 ohms	11.4 cm(4.495")	4.214 cm(1.659")
10.16 cm(4")	15.6 cm(6.13")	75 ohms	12.6 cm(4.962")	3.386 cm(1.333")

*Z_o represents the characteristic impedance of Section 1 when empty.

FIGURE 1. 4" SAMPLE HOLDER, DROP MECHANISM AND DEPTH GUAGE

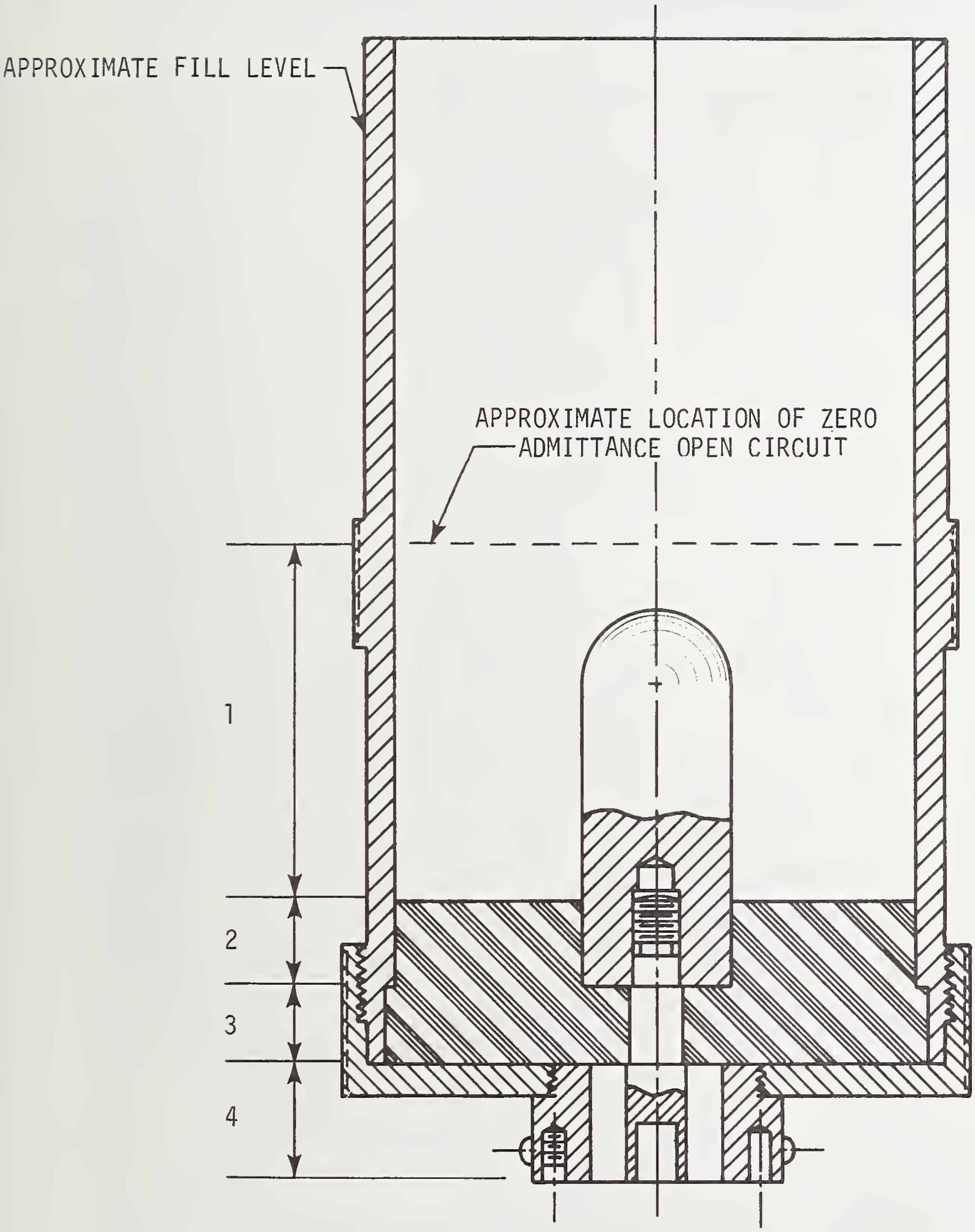


FIGURE 2. CROSS SECTION OF DIELECTRIC SAMPLE HOLDER SHOWING COAXIAL SECTIONS 1, 2, 3, AND 4.

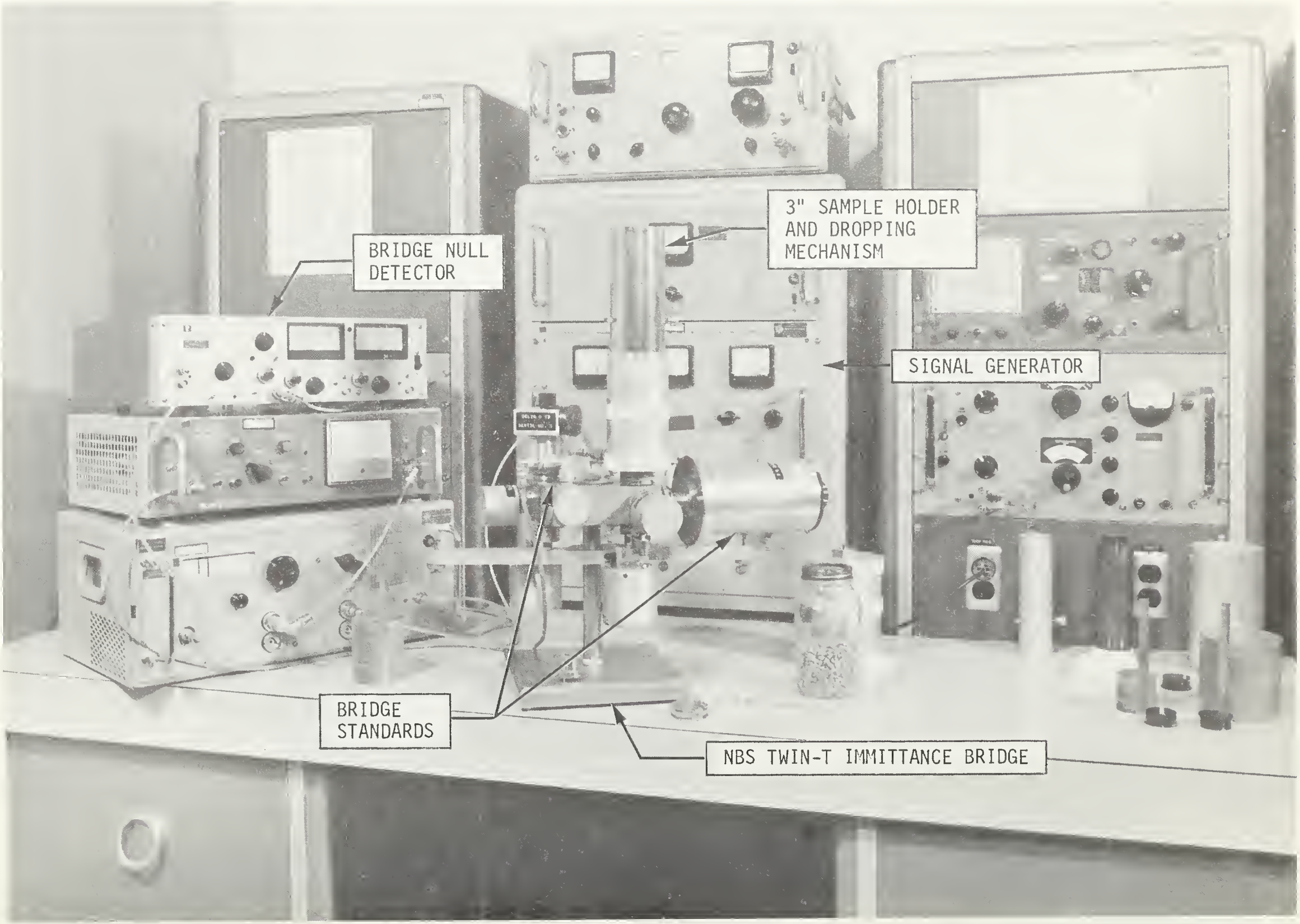


FIGURE 3. BRIDGE SET UP FOR MEASUREMENTS AT 1 MHz

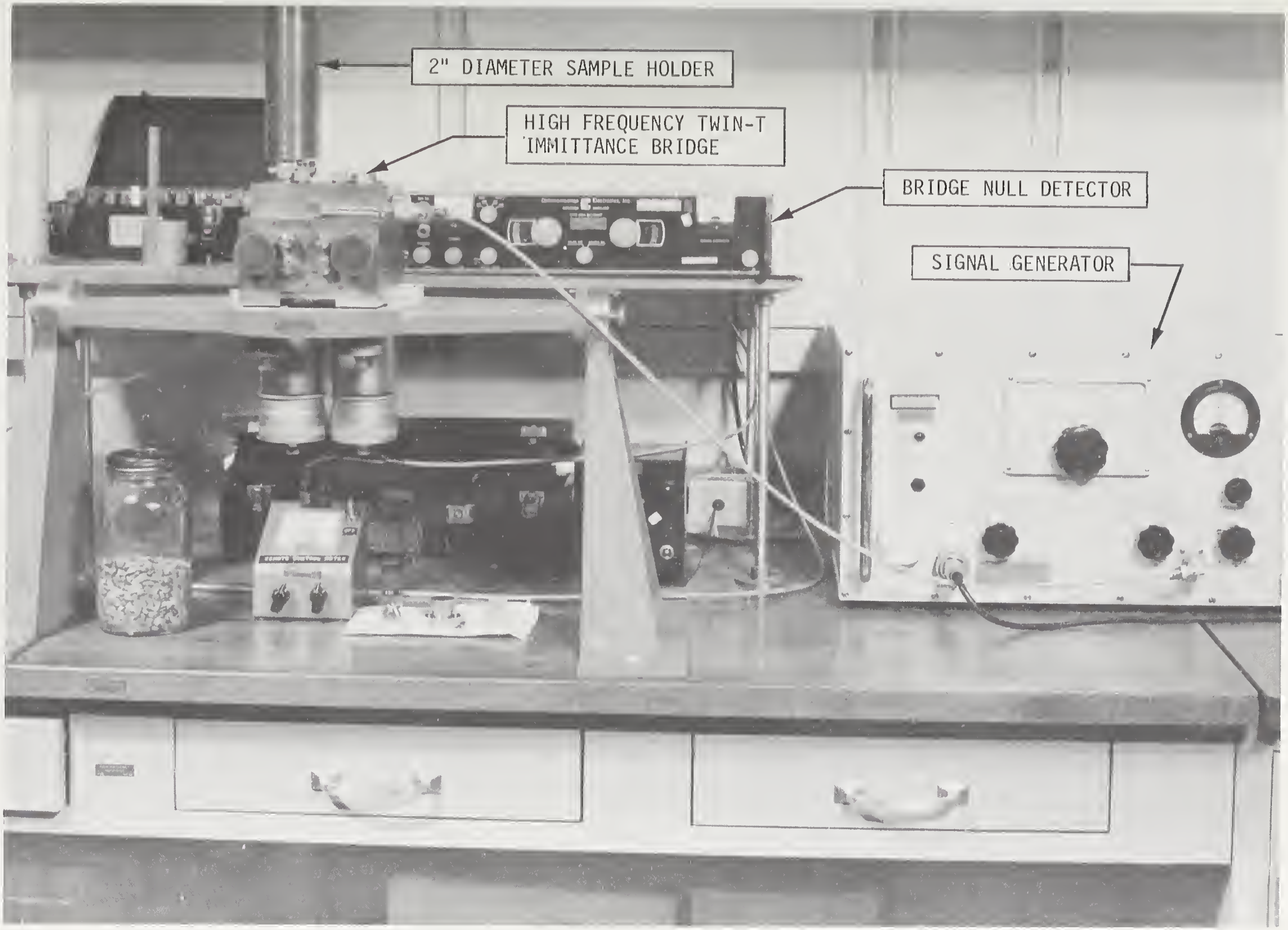


FIGURE 4. BRIDGE SET UP FOR MEASUREMENTS FROM 5 TO 200 MHz

6. MEASUREMENT THEORY

At low frequencies, 1 MHz or below, we may use electrostatics; then the admittance of a capacitive circuit such as a sample holder containing a dielectric material can be expressed as

$$Y_s = G + j\omega\varepsilon^*C \tag{1}$$

where G = the effective conductance between the electrodes including the series resistance of the structure,
ω = angular frequency,
C = capacitance in vacuum between electrodes of the sample holder,
and $\varepsilon^* = \varepsilon' - j\varepsilon''$, the complex dielectric constant of the dielectric material in the sample holder. Using the complex form of the dielectric constant, expression (1) becomes

$$Y_s = G + j\omega C(\varepsilon' - j\varepsilon'') \tag{2}$$

which reduces to

$$Y_s = (G + \omega\varepsilon''C) + j\omega\varepsilon'C \ . \tag{3}$$

To determine the complex dielectric constant of the material in the sample holder, the admittance of the empty (air filled) sample holder is subtracted. Assuming the structure losses are unchanged from the filled condition and the complex dielectric constant of air is 1, the empty admittance is

$$Y_e = G + j\omega C \ . \tag{4}$$

This gives, for the admittance difference between the full and empty conditions

$$\Delta Y = Y_s - Y_e = \Delta G + j\omega\Delta C = \varepsilon''\omega C + j\omega C(\varepsilon'-1) \ . \tag{5}$$

Equating real and imaginary parts from each side of the equation gives

$$\varepsilon' = 1 + \frac{\Delta C}{C} \text{ for dielectric constant,} \tag{6}$$

$$\text{and} \quad \varepsilon'' = \frac{\Delta G}{\omega C} \quad \text{for loss factor.} \tag{7}$$

By definition, the loss tangent of the material in the sample holder is $\tan\delta = \frac{\varepsilon''}{\varepsilon'}$. (8)

Thus the dielectric properties of a material, such as grain, can be determined from the difference between the admittances of the full and empty sample holder.

At low frequencies where the dimensions of the sample holder are sufficiently small with respect to a quarter wavelength, the computation procedure is simple, and the dielectric properties are easily obtained by simply substituting measured admittance values for the empty and full sample holder into eqs (6) and (7). However, this assumption leads to large errors as the measurement frequency is increased and a modified computation procedure is used in the 1 to 200 MHz range. This procedure is described in the following section.

7. HIGHER FREQUENCY MEASUREMENT THEORY AND COMPUTATION PROCEDURE

At higher frequencies the concept of simple coaxial capacitors does not apply. The measurable quantity at the interface with the measuring instrument (bridge), or at any transverse plane, is the admittance, reference [5], defined as the ratio of longitudinal current to transverse voltage for the TEM mode of a coaxial line. This definition reduces to the admittance used in equations (1) and (5) as the frequency approaches zero.

In order to calculate the dielectric constant and loss of the sample from the measured admittance, Y_m, we must obtain the theoretical admittance as a function of the propagation constant, the distance, d, and the TEM characteristic admittance,

$$Y_c = 2\pi \ (\varepsilon_o \varepsilon^*/\mu_o)^{\frac{1}{2}}/\ell n(b/a), \tag{9}$$

where b and a are radii of the tube and the center conductor respectively, μ_o and ε_o are the permeability and permittivity of vacuum, and ε^* was defined for (1).

The theoretical admittance at the plane of measurement is predicted by transforming the admittance from the plane of the open circuit of section 1 to the bottom of section 4. The relative admittance, y_e, at the top (output) end of any section of line is transformed to the input (generator) end of the same section by the equation

$$y_{in} = (1 + y_e \coth \gamma d)/(\coth\gamma d + y_e), \tag{10}$$

where y_{in} is the relative input admittance, γ is the complex propagation constant in the section, and d is the length of the section. The term relative admittance means that the absolute admittance has been divided by the characteristic admittance, eq (9). Both Y_c, and $\gamma = (-\omega^2\mu_o\varepsilon_o\varepsilon^*)^{\frac{1}{2}}$, depend upon the complex permittivity ε^* of the section. ω is the radian frequency.

Equation (10) is applied four times to transform the admittance from the open circuit to the measurement plane. The absolute admittance at a dielectric interface is continuous except when changes in radii a and b occur. Then the shunt admittance of the step $Y_{step} = j\omega \ C_{step} \ \varepsilon^*$ must be added. C_{step} is given in reference [3]. With air in section 1 the measured admittance Y_m is used to check that all quantities, e.g., section lengths, dielectric constants, Y_c, Y_{step}, are correct, and that the known $\varepsilon^* = 1$ results for air.

To evaluate ε^* of an unknown dielectric in section 1 we use eq (10) with $y_e = 0$ at the plane of the effective open circuit, $d = d_1 + d'$, where d' is the added distance [4] beyond the end of the center conductor to the effective open circuit, and y_{in} is obtained from measured Y_m of section 4 by transforming backward from the bridge measurement plane to the input of section 1, using eq (10) in the known invariant sections, 4, 3, 2. The transcendental equation to be solved using (10) again is

$$y_{in} = Y_m'/Y_C = \tanh \gamma(d_1 + d'), \tag{11}$$

where the complex unknown ε^* appears both in Y_C and in γ. Y_m' is the admittance that would have been measured at the input of section 1. To find a solution we start with an estimated ε^* in (11) and iterate by Newton's method until the equation is satisfied. The equation has multiple roots but at low frequencies, with grain as the dielectric, only the lowest root is reasonable.

A correction is required in d_1 of eq (11) for the spherically tapered end. Only the flatly truncated center conductor is treated in references [3] and [4]. We assume that the terminating capacitance [3] and the equivalent extension [4] are still just the same as for the flat ended conductor, and then we subtract a small quantity from the true physical length of section 1. The amount subtracted is approximately 37% of the radius of the center conductor. This method was found to be valid experimentally (over the required frequency range), i.e., dielectric measurements of known materials, e.g., air and carbon tetrachloride, were correct and were the same as when a flat ended termination was used.

The electric field which extends beyond the end of section 1 interacts with the dielectric sample and contributes to the measured admittance Y_m. This is correctly taken into account in the above method. Not only does γ contain ε' but also the extended distance d' in d depends on ε'. d' was adjusted for the value of ε' during the Newton iterations. A correction for the loss ε'' was not used in d'. More work would be required to find the effect of ε'', and this remains to be done.

Finally, since the field extends beyond the center termination, we need to calculate how far the grain sample should extend. Theoretically it should extend to infinity. Practically, if the hollow tube is well below cutoff, i.e.,

$$\varepsilon' \ll [.387c/(bf)]^2 , \tag{12}$$

where f is the frequency in hertz, b is the radius of the hollow tubing, and c is the velocity of light in the same length units, then the sample needs to extend beyond the center conductor only a distance of 1.5 b. The evanescent field in the tube decays as exp(-2.405z/b) where z is distance beyond the end of the center conductor. To a good approximation, the material in the region beyond z = 1.5 b is unimportant if eq (12) is true.

Table 1 gives some dimensions of the three holders. The impedance Z_o may be obtained from the inverse of Y_c in eq (9).

8. ACCURACY OF ε' AND TAN δ MEASUREMENTS

To verify the measurement data from the sample holders, standard liquids were measured. These included carbon tetrachloride (CCl_4) and chlorobenzene (C_6H_5Cl). These liquids have for their ε' values 2.232 and 5.656 respectively at 23°C according to Buckley and Maryott [8]. Measurements from 1 kHz to 200 MHz yielded results which agreed with accepted values to within ± 0.3 percent.

An assessment of the error in ε' due to the error in bridge admittance was carried out by computing the changes in ε' resulting from inputting known admittance increments into the computer program. This yielded very nearly a one-to-one correspondence between the percentage capacitance error and the resulting percentage change in the value arrived at for ε'-1 (see eq 6).

A characteristic of the high frequency Twin-T bridge [6] is that the sensitivity is somewhat reduced near the low end of its frequency range and circuit residual immittances introduce uncertainties at the upper end of its frequency range. As a result, the capacitance uncertainty is considered to be ± 0.2 percent at 5 MHz and also in the region above 100 MHz, with uncertainties of ± 0.1 percent in the intermediate region. The Twin-T bridge used for the 1 MHz measurements [7] has an uncertainty of ± 0.1 percent.

Tan δ values are generally not measurable to the same accuracy, especially as the value of tan δ becomes smaller. In general the tan δ values of the samples ranged from 0.1 to 1. Over this region, for the bridges used, the uncertainties for tan δ would vary from ± 0.15 percent to 1 percent in the frequency range where the bridge uncertainty was ± 0.1 percent, and from ± 0.3 percent to 2 percent in the frequency range where the bridge uncertainty was ± 0.2 percent. In the foregoing statement the larger uncertainties apply to the smaller values of tan δ and vice versa.

As a generalized conclusion to the foregoing uncertainty discussion, it is believed that the absolute uncertainty of the values for ε' and tan δ given in the data are approximately ± 0.5 percent for ε', ± 1 percent for tan δ from 10 to 100 MHz, and ± 2 percent for tan δ at 5 MHz and above 100 MHz. The uncertainty of the tan δ values at 1 MHz is approximately ± 1 percent. These error bounds of course do not include the nonrepeatability due to packing density variations.

9. UNSETTLED AND SETTLED VALUES

To examine the effect of density (or settling) upon the values for dielectric constant and loss tangent, a procedure was adopted for adding the grain to the sample holder and also for settling the grain in a consistent manner. The center object in figure 1 is a dropping container arranged to set atop the sample holder (shown on the left). Inside the dropping container is a collapsible metal diaphragm which, upon release, allows the grain sample to drop into the sample holder. All values in this report that are designated "unsettled" were taken immediately after the sample was dropped into the holder in this manner.

After the grain was dropped into the holder and an admittance measurement was taken, the grain-filled holder was removed from the bridge and subjected to a vibration procedure which was performed in two stages. The first stage consisted of bumping the side of the sample holder with the heel of the operator's hand one hundred times in quick succession. This was followed by the application of a small vibrator to the side of the sample holder for a period of 30 seconds. Following this procedure the grain-filled sample holder was reconnected to the bridge, and a second admittance measurement was taken. Values in the report designated "settled" were obtained after this procedure was performed.

The wooden plug with attached scale (shown on the right) was used to measure the level of the grain in the holder, both before and after the settling procedure. All admittance values were taken with the wooden plug removed from the holder. It is noted here that the presence of the plug in the holder made no significant difference in the bridge admittance reading because the grain samples were made large enough so that the electric field region inside the holder was entirely filled by grain. In a later portion of this report the effect of adding weight to the grain surface is discussed.

The settling procedure just described was repeated several times on various samples of corn, wheat, and soya, and after the first settling procedure, repeated vibrating did not bring about significant additional changes in the observed values of ε' and $\tan \delta$.

A logarithmic mixing rule by Lichtenecker, which is discussed in Von Hippel [9], is used to determine the permittivity ε' of a mixture from ε_1' and ε_2' and the volume fractions θ_1 and θ_2 of the components:

$$\log \varepsilon' = \theta_1 \log \varepsilon_1' + \theta_2 \log \varepsilon_2' \ . \tag{13}$$

In this instance one of the components is air which essentially has a relative permittivity of 1. Unfortunately, there is no convenient or accurate method of determining the volume ratios of the air and the grain so this rule is of no direct benefit in determining the permittivity of the grain. However, it is assumed that the dielectric properties of an average kernel of grain, at a given time are constant. Therefore, from equation (9) we can write for the relationship between dropped and settled conditions:

$$\frac{\log \varepsilon_d'}{P_d} = \frac{\log \varepsilon_s'}{P_s} \ , \tag{14}$$

where P_d and P_s are the dropped and settled densities, respectively. This being true, it would be possible to arrive at a consistent value for the permittivity provided the packing density of the mixture were measured, and in this way errors due to density variations could be removed.

To test the foregoing hypothesis, data from measurements at 1 and 30 MHz on wheat, corn, and soya at various percentage moisture levels were examined. These data are shown in tables 2 through 7. In the tables the values shown under the "%" heading are the percentage moisture levels as determined by the oven-dry process. In all cases, in tables 2 through 7, the settled values were derived after one execution of the settling procedure. As previously mentioned the values P_1 and P_2 were the density values determined before and after settling. The percentages shown in the right-hand column of tables 2 through 7 are uncertain by an estimated ± 1.5. This uncertainty includes a measurement uncertainty of ± 0.5 percent in the measured values for ε_1' and ε_2', and an uncertainty of ± 0.25 cm (0.1 inch) in the depth gauge measurement of the fill level in the sample holder. The depth measurement was hampered by the uneven grain surface, but to reduce error the gauge plug was rotated through 360° while setting on the grain to smooth and level the surface. If the relationship of eq (10) were perfectly valid, the numbers in the right-hand columns of tables 2 through 7 would all have been zero. The fact that the variations from zero are fairly evenly distributed in both magnitude and direction shows no definite departure from eq (10). However, it does not present a reliable method for density corrections when measuring an individual sample. The reason for the one very large value in table 4 may be due to an erroneous data point.

Another aspect of the question of settling is whether a settling procedure, such as the one described, improves the ability to reproduce a given sample density. The data in tables 8, 9, and 10 pertain to this question. Here the average density values and their standard deviations are tabulated for all of the settling operations performed. The three tables give data for corn, wheat, and soya. Overall, the standard deviations are smaller for the density of the dropped grain than for the settled grain, and the dropping procedure, in addition to being more convenient, is probably superior in obtaining repeatable measurements of dielectric constant.

Table 2.

$$C_1 = \frac{\log e_1'}{P_1} \; ; \; C_2 = \frac{\log e_2'}{P_2}$$

Grain	%	C_1	C_2	$\frac{C_2-C_1}{C_1} \times 100$	
Corn	17.7	1.121	1.164	3.8 ± 1.6	
Corn	23.3	1.409	1.391	-1.3	
Corn	26.0	1.378	1.395	1.2	All Data
Corn	29.0	1.820	1.745	-4.1	taken at 1 MHz
Corn	30.9	1.902	1.850	-2.7	
Corn	34.0	2.140	2.130	-0.47	
Corn	8.5	0.762	0.769	0.92	
Corn	10.4	0.804	0.834	3.7	
Corn	12.9	0.910	0.919	0.9	All Data
Corn	15.8	1.032	1.028	-0.3	taken at 1 MHz
Corn	19.1	1.213	1.216	0.25	
Corn	22.4	1.409	1.397	-0.85	
Corn	25.7	1.604	1.549	-3.4	Data taken in
Corn	28.6	1.727	1.740	0.7	reverse order
Corn	30.9	1.943	1.909	-1.7	(bottom to top)
Corn	33.7	2.126	2.086	-1.9	as grain dried
Corn	39.0	2.481	2.469	-0.4	from 39% to 8.5%

Table 3.

$$C_1 = \frac{\log \varepsilon_1'}{P_1} \; ; \; C_2 = \frac{\log \varepsilon_2'}{P_2}$$

Grain	%	C_1	C_2	$\frac{C_2-C_1}{C_1} \times 100$	
Wheat	10.7	0.769	0.768	-0.13	
Wheat	13.4	0.827	0.849	2.6	
Wheat	14.3	0.866	0.859	-0.81	
Wheat	16.0	0.939	0.955	1.7	All Data
Wheat	16.6	0.973	0.970	-0.31	taken at 1 MHz
Wheat	18.4	1.012	0.980	-3.3	
Wheat	18.5	1.089	1.096	0.64	
Wheat	21.2	1.194	1.202	0.67	

Table 4.

$$C_1 = \frac{\log \varepsilon'_1}{P_1} \; ; \; C_2 = \frac{\log \varepsilon'_2}{P_2}$$

Grain	%	C_1	C_2	$\frac{C_2 - C_1}{C_1} \times 100$	
Soya	10.4	0.842	0.835	-0.84	
Soya	10.4	0.755	0.831	10	
Soya	11.4	0.908	0.937	3.1	
Soya	11.4	0.917	0.948	3.3	
Soya	13.1	0.951	0.992	4.3	All Data
Soya	13.9	1.098	1.104	0.55	taken at 1 MHz
Soya	14.5	1.032	1.078	4.5	
Soya	14.8	1.116	1.149	3.0	
Soya	16.1	1.200	1.250	4.2	
Soya	16.9	1.278	1.310	2.5	

Table 5.

$$C_1 = \frac{\log \varepsilon'_1}{P_1} \; ; \; C_2 = \frac{\log \varepsilon'_2}{P_2}$$

Grain	%	C_1	C_2	$\frac{C_2 - C_1}{C_1} \times 100$	
Corn	17.7	0.983	0.974	-0.91	
Corn	23.3	1.082	1.100	1.7	
Corn	26.0	1.113	1.155	3.8	All Data
Corn	29.0	1.203	1.250	3.9	taken at 30 MHz
Corn	30.9	1.380	1.332	-3.5	
Corn	34.0	1.356	1.377	1.5	
Corn	8.5	0.679	0.677	- .29	
Corn	10.4	0.728	0.741	1.8	
Corn	12.9	0.814	0.834	2.5	
Corn	15.8	0.908	0.899	-0.99	
Corn	19.1	0.999	1.004	0.50	
Corn	22.4	1.071	1.077	0.56	All Data
Corn	25.7	1.164	1.154	-0.86	taken at 30 MHz
Corn	28.6	1.221	1.231	0.82	
Corn	30.9	1.302	1.303	0.08	
Corn	33.7	1.355	1.343	-0.89	
Corn	39.0	1.524	1.528	0.26	

Table 6.

$$C_1 = \frac{\log \varepsilon'_1}{P_1} \; ; \; C_2 = \frac{\log \varepsilon'_2}{P_2}$$

Grain	%	C_1	C_2	$\frac{C_2 - C_1}{C_1} \times 100$	
Wheat	10.7	0.684	0.687	0.44	
Wheat	13.4	0.757	0.764	0.92	
Wheat	14.3	0.765	0.775	1.3	
Wheat	16.0	0.834	0.843	1.1	All Data
Wheat	16.6	0.868	0.857	-1.3	taken at 30 MHz
Wheat	18.4	0.890	0.891	0.11	
Wheat	18.5	0.889	0.891	0.22	
Wheat	21.2	0.991	0.985	-0.61	

Table 7.

$C_1 = \frac{\log \varepsilon_1'}{P_1}$; $C_2 = \frac{\log \varepsilon_2'}{P_2}$

Grain	%	C_1	C_2	$\frac{C_2-C_1}{C_1} \times 100$	
Soya	10.4	0.701	0.725	3.4	
Soya	10.4	0.682	0.713	4.5	
Soya	11.4	0.745	0.775	4.0	
Soya	11.4	0.746	0.750	0.54	
Soya	13.1	0.796	0.808	1.5	All Data
Soya	13.9	0.853	0.873	2.3	taken at 30 MHz
Soya	14.5	0.832	0.858	3.1	
Soya	14.8	0.886	0.919	3.7	
Soya	16.1	0.918	0.955	4.0	
Soya	16.9	0.956	1.003	4.9	

Table 8. The effect of settling on the density of corn.

Grain	% Moisture	No. of Drops & Settlings	Average Density in g/cc ± Standard Deviation Dropped	Settled
Corn	17.7	8	0.668 ± 0.0075	0.715 ± 0.010
Corn	23.3	8	0.608 ± 0.0028	0.678 ± 0.0028
Corn	26.0	8	0.638 ± 0.0053	0.690 ± 0.010
Corn	29.0	8	0.522 ± 0.0072	0.578 ± 0.010
Corn	30.9	8	0.510 ± 0.0065	0.574 ± 0.011
Corn	34.0	8	0.510 ± 0.0059	0.570 ± 0.0057
Corn	8.5	7	0.611 ± 0.0032	0.637 ± 0.0088
Corn	10.4	8	0.616 ± 0.0077	0.640 ± 0.0058
Corn	12.9	8	0.619 ± 0.0057	0.648 ± 0.0097
Corn	15.8	7	0.608 ± 0.0081	0.651 ± 0.0054
Corn	19.1	7	0.587 ± 0.0051	0.639 ± 0.0039
Corn	22.4	7	0.556 ± 0.0049	0.617 ± 0.0037
Corn	25.7	7	0.534 ± 0.0035	0.599 ± 0.0047
Corn	28.6	8	0.517 ± 0.0058	0.580 ± 0.0037
Corn	30.9	8	0.510 ± 0.0063	0.570 ± 0.0061
Corn	33.7	8	0.503 ± 0.0064	0.564 ± 0.0087
Corn	39.0	8	0.504 ± 0.0036	0.569 ± 0.0038

Table 9. The effect of settling on the packing density of wheat.

Grain	% Moisture	No. of Drops & Settlings	Average Density in g/cc ± Standard Deviation Dropped	Settled
Wheat	10.7	6	0.828 ± 0.0015	0.889 ± 0.0044
Wheat	13.4	5	0.809 ± 0.0035	0.862 ± 0.0093
Wheat	14.3	6	0.798 ± 0.0090	0.842 ± 0.0018
Wheat	16.0	5	0.777 ± 0.0046	0.832 ± 0.0018
Wheat	16.6	6	0.721 ± 0.0032	0.789 ± 0.0035
Wheat	18.4	5	0.745 ± 0.0068	0.818 ± 0.0036
Wheat	18.5	6	0.731 ± 0.0134	0.781 ± 0.0122
Wheat	21.2	5	0.692 ± 0.0043	0.762 ± 0.0078

Table 10. The effect of settling on the packing density of soya.

Grain	% Moisture	No. of Drops & Settlings	Average Density in g/cc ± Standard Deviation Dropped	Settled
Soya	10.4	8	0.710 ± 0.0104	0.755 ± 0.0081
Soya	10.4	8	0.723 ± 0.0038	0.756 ± 0.0047
Soya	11.4	8	0.716 ± 0.0060	0.750 ± 0.0086
Soya	11.4	8	0.721 ± 0.0043	0.763 ± 0.0078
Soya	13.1	8	0.700 ± 0.0025	0.740 ± 0.0104
Soya	13.9	8	0.703 ± 0.0049	0.746 ± 0.0094
Soya	14.5	8	0.714 ± 0.0057	0.754 ± 0.0056
Soya	14.8	8	0.681 ± 0.0072	0.728 ± 0.0104
Soya	16.1	8	0.677 ± 0.0049	0.720 ± 0.0052
Soya	16.9	8	0.673 ± 0.0035	0.720 ± 0.0081

10. DATA AND DISCUSSION

To provide an accessible quantity of data for future use, the tables of Appendix 1 containing essentially all of the data accumulated during this phase of the project are provided. The data are for corn, wheat, and soya at various moisture levels, and values of ε', tan δ and ε'' are given for both the dropped and settled condition at various frequencies, including 1, 5, 10, 30, 50, 100, 150, and 200 MHz.

It should be noted that the grain samples were cycled through the dropping and settling procedure at each frequency at which data are given. Had an automated measurement system been available covering this frequency range and providing comparable accuracy and resolution, rehandling of the grain between each measurement frequency would not have been necessary and much time could have been saved. Although this would have been beneficial in one respect, it would likely have shown a different set of results than appears here because the data from all of the measurement frequencies would have been taken after one dropping and settling procedure so that the plots of a single run would have shown less inconsistency. The data tabulated here do not provide smooth curves because of the nonrepeatability of the dielectric parameters from one time the grain is put into the holder to another. Nevertheless, the value of an automated impedance measurement system would have been appreciable because much more data could have been accumulated in the same time period.

An estimate of the uncertainty in the moisture content (by oven drying) of the various grain samples is not given. Upon examination of the various plots included on the succeeding pages, it is evident that errors in measurement of moisture content may be present. This is discussed in greater detail in 10.1.

10.1 ε' and Tan δ as a Function of Percent Moisture Content

A particular effort was made with respect to high moisture corn, and these results will be discussed first. Experiments were carried out in two phases. In one phase a sizeable sample of corn was gathered shortly before harvest from a field in central Colorado. When gathered, this corn was at approximately 40 percent. Measurements from this corn sample were made every few days at a number of frequencies as the corn was allowed to air dry down to a moisture level of 8.5 percent. Figures 5 and 6 show ε' for eleven moisture levels between 39 percent and 8.5 percent for frequencies of 1, 5, 10, 30, and 200 MHz for both dropped and settled samples. Although the plots are neither linear nor log normal, they do appear to yield a fairly smooth curve over this moisture range.

As mentioned earlier, the standard for grain moisture measurement is an oven-dry process which has been developed to its present state by the U.S.D.A. Grain Standardization Laboratory in Beltsville, Maryland. All of the percentage moisture levels given in this report were determined by the Beltsville laboratory prior to shipment to the NBS labs in Boulder, Colorado, where the dielectric measurements were performed. For shipment the grain samples were sealed in 0.015 cm (0.006") thick plastic bags to retard moisture gain or loss. Once received at Boulder, the grain was weighed out in appropriate sample sizes

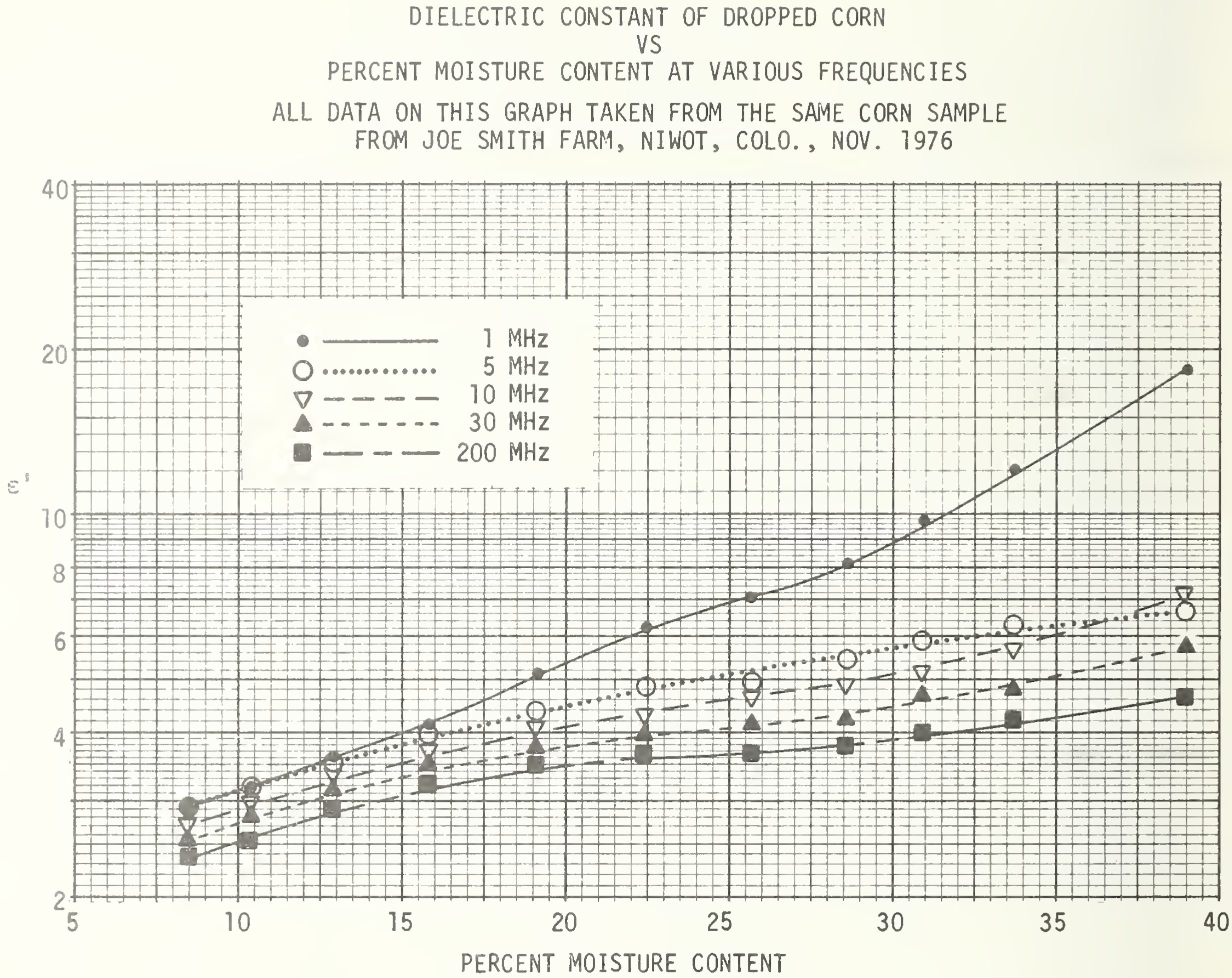
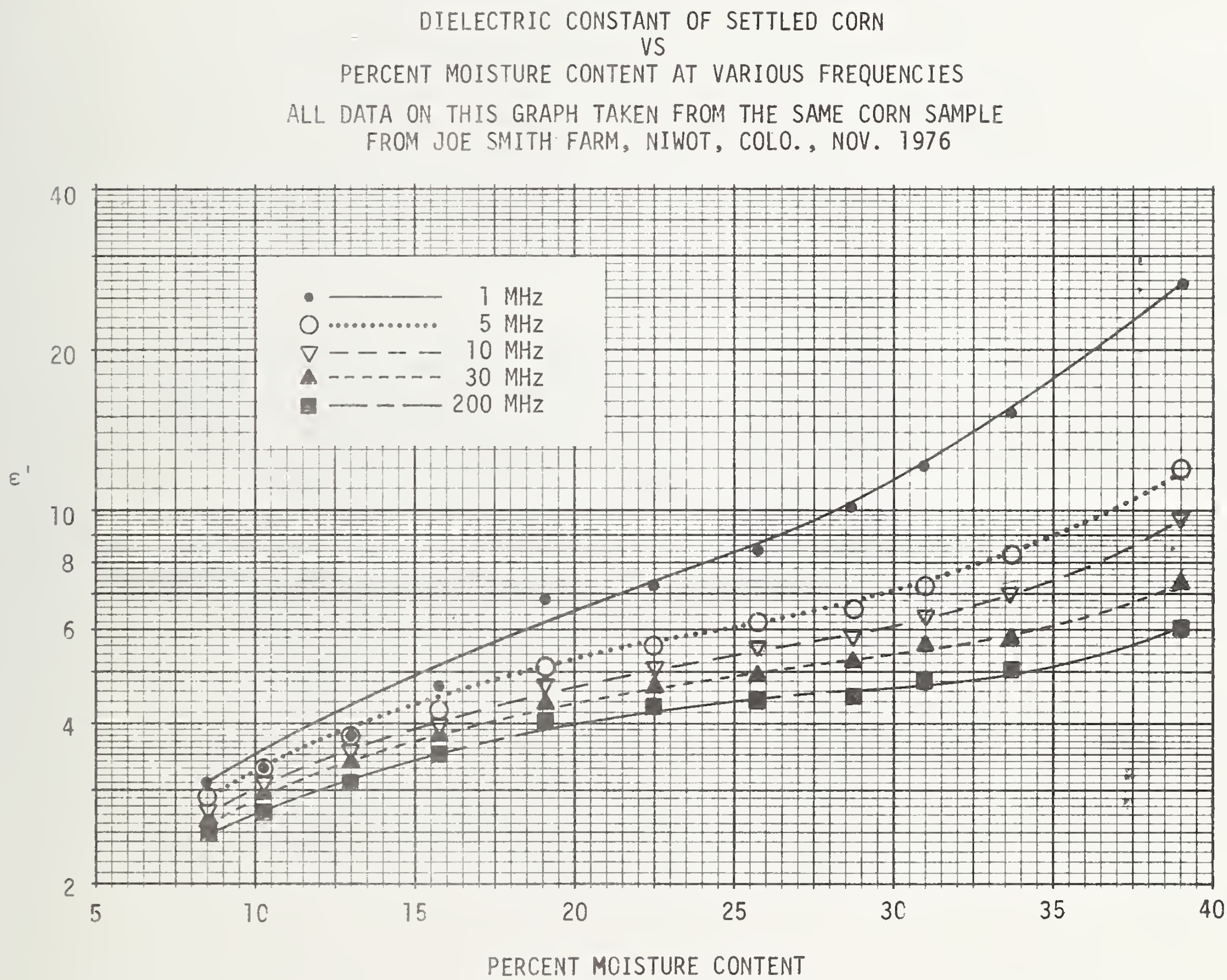

DIELECTRIC CONSTANT OF DROPPED CORN
VS
PERCENT MOISTURE CONTENT AT VARIOUS FREQUENCIES
ALL DATA ON THIS GRAPH TAKEN FROM THE SAME CORN SAMPLE
FROM JOE SMITH FARM, NIWOT, COLO., NOV. 1976
1 MHz
5 MHz
10 MHz
30 MHz
200 MHz
ε'
40
20
10
8
6
4
2
5
10
15
20
25
30
35
40
PERCENT MOISTURE CONTENT

Figure 5.



DIELECTRIC CONSTANT OF SETTLED CORN
VS
PERCENT MOISTURE CONTENT AT VARIOUS FREQUENCIES
ALL DATA ON THIS GRAPH TAKEN FROM THE SAME CORN SAMPLE
FROM JOE SMITH FARM, NIWOT, COLO., NOV. 1976
1 MHz
5 MHz
10 MHz
30 MHz
200 MHz
ε'
40
20
10
8
6
4
2
5
10
15
20
25
30
35
40
PERCENT MOISTURE CONTENT

Figure 6.

and the dielectric characteristics measured as quickly as possible. The dielectric measuring procedure often required a day or more to complete, and during this time the grain samples were kept in sealed glass jars and under refrigeration when not actually being subjected to the measurement process. In spite of these precautions against change in sample moisture content following the oven-dry determination, some changes may have occurred during shipment of the samples from one laboratory to the other. The shipping time duration was generally from two to five days; and, while in transit through the mails, they could have been subjected to some fairly wide temperature excursions. Future experiments should include precautionary procedures which would preclude errors in the values finally used for percent moisture content. The advisability of having the oven-dry facility located at the same place as the electrical measurement facilities seems obvious. This would avoid the need for shipping, packing, extra handling, and time lapse between the two experiments which may have resulted in some errors in the final data.

A similar experiment was carried out using six corn samples supplied by the U.S.D.A. These samples came from random locations around the country and were of various hybrid varieties. Figures 7 and 8 show ε' as a function of moisture content for the same five frequencies as before, but there is much less tendency for the results to follow a predictable pattern or behavior law. There is probably very little that can be definitely concluded from these relatively brief experiments, except that different hybrid characteristics or growing conditions add an extra dimension of uncertainty to the dielectric behavior of the grain. Figures 9 through 12 show similar plots for randomly gathered samples of wheat and soya. These also exhibited some inconsistent behavior of ε' as a function of percent moisture content.

Figures 13 through 28 are plots of loss tangent and loss factor which correspond to the dielectric constant data in figures 5 through 12. In general this data supports previous observations by other researchers indicating that grain coming from different locations does not demonstrate the consistent dielectric constant versus percent moisture characteristics. This brings about the need for local control and is currently being done by the U.S.D.A.

A notable phenomenon in the loss tangent data is the crossover of the frequency plots in the 10 to 20 percent moisture region, which is noticeable in the corn and wheat data. This would make it imperative that all moisture testing be done at the same frequency if loss tangents were to be employed as the indicating parameter.

DIELECTRIC CONSTANT OF DROPPED CORN
VS
PERCENT MOISTURE CONTENT AT VARIOUS FREQUENCIES

CORN TAKEN FROM MISCELLANEOUS LOCATIONS IN U.S.A.

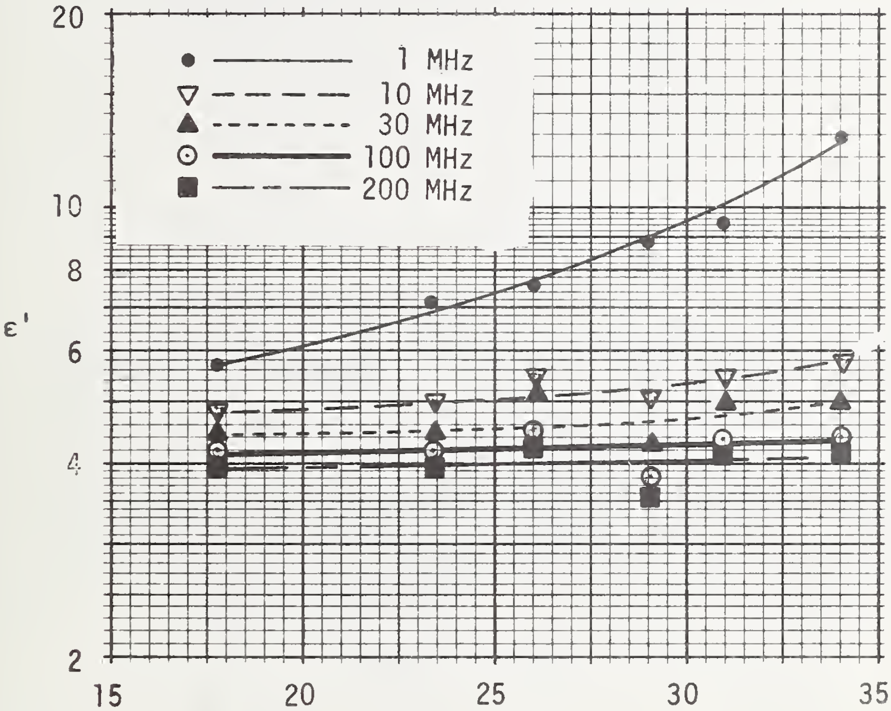


Figure 7.

DIELECTRIC CONSTANT OF SETTLED CORN
VS
PERCENT MOISTURE CONTENT AT VARIOUS FREQUENCIES
CORN TAKEN FROM MISCELLANEOUS LOCATIONS IN U.S.A.

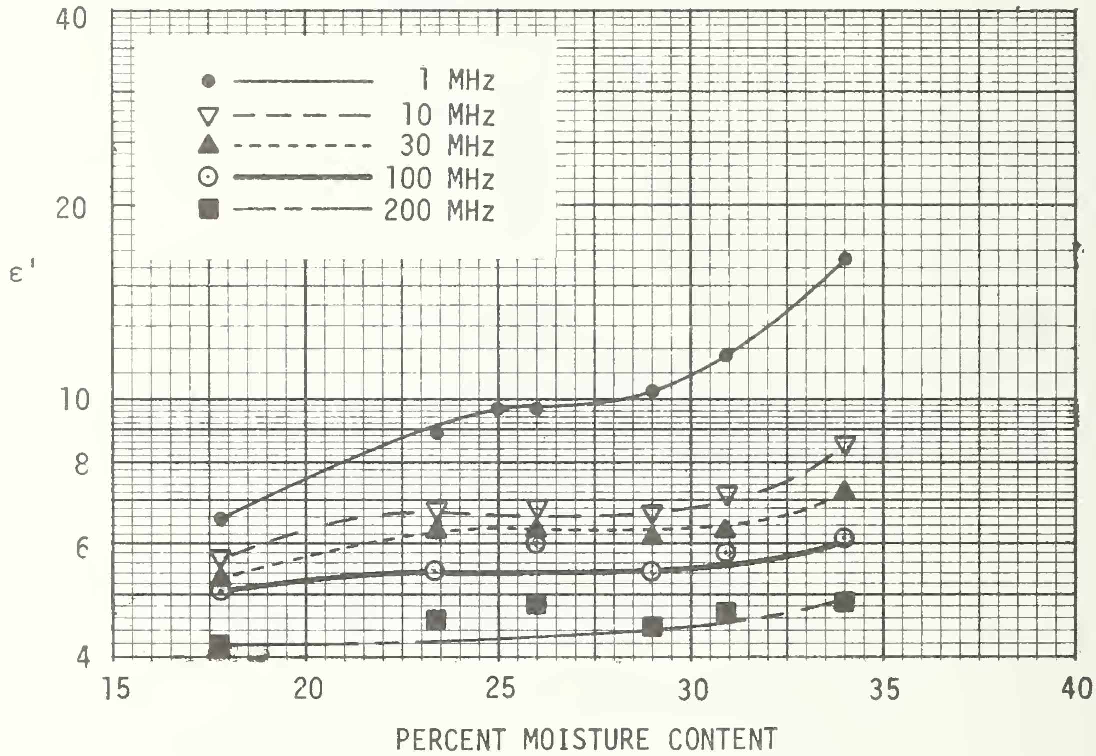


Figure 8.

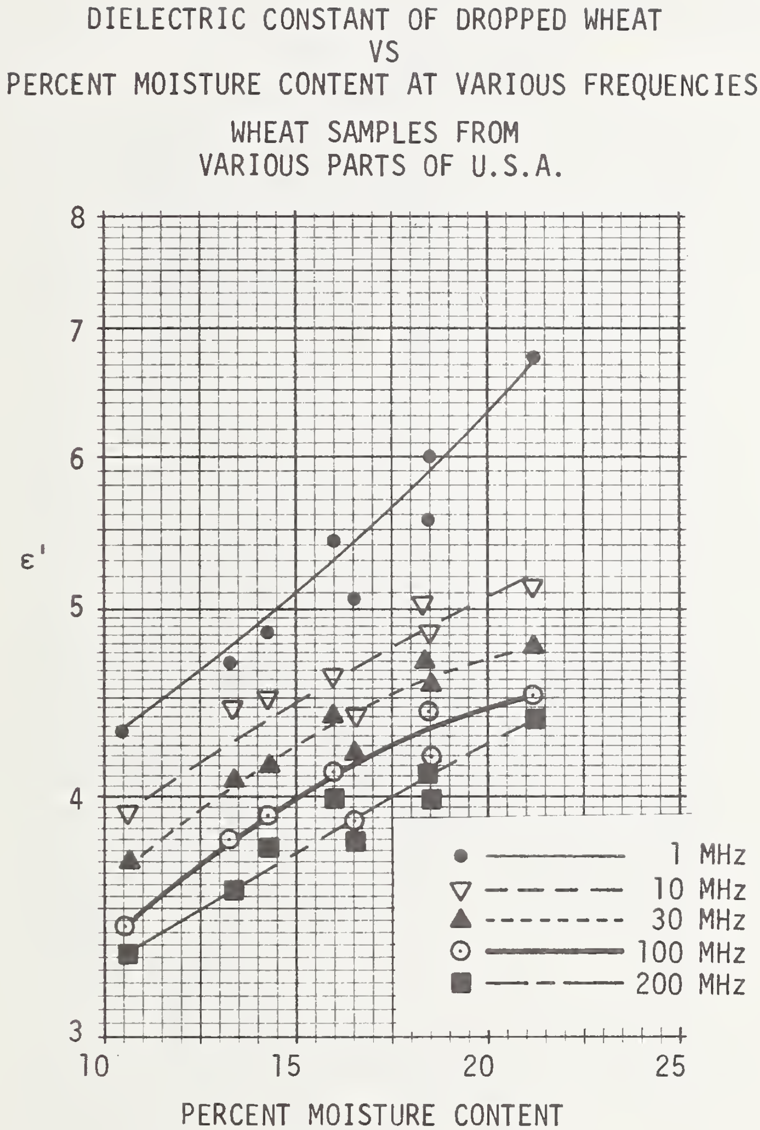

DIELECTRIC CONSTANT OF DROPPED WHEAT
VS
PERCENT MOISTURE CONTENT AT VARIOUS FREQUENCIES
WHEAT SAMPLES FROM
VARIOUS PARTS OF U.S.A.
ε'
8
7
6
5
4
3
10
15
20
25
PERCENT MOISTURE CONTENT
1 MHz
10 MHz
30 MHz
100 MHz
200 MHz

Figure 9.

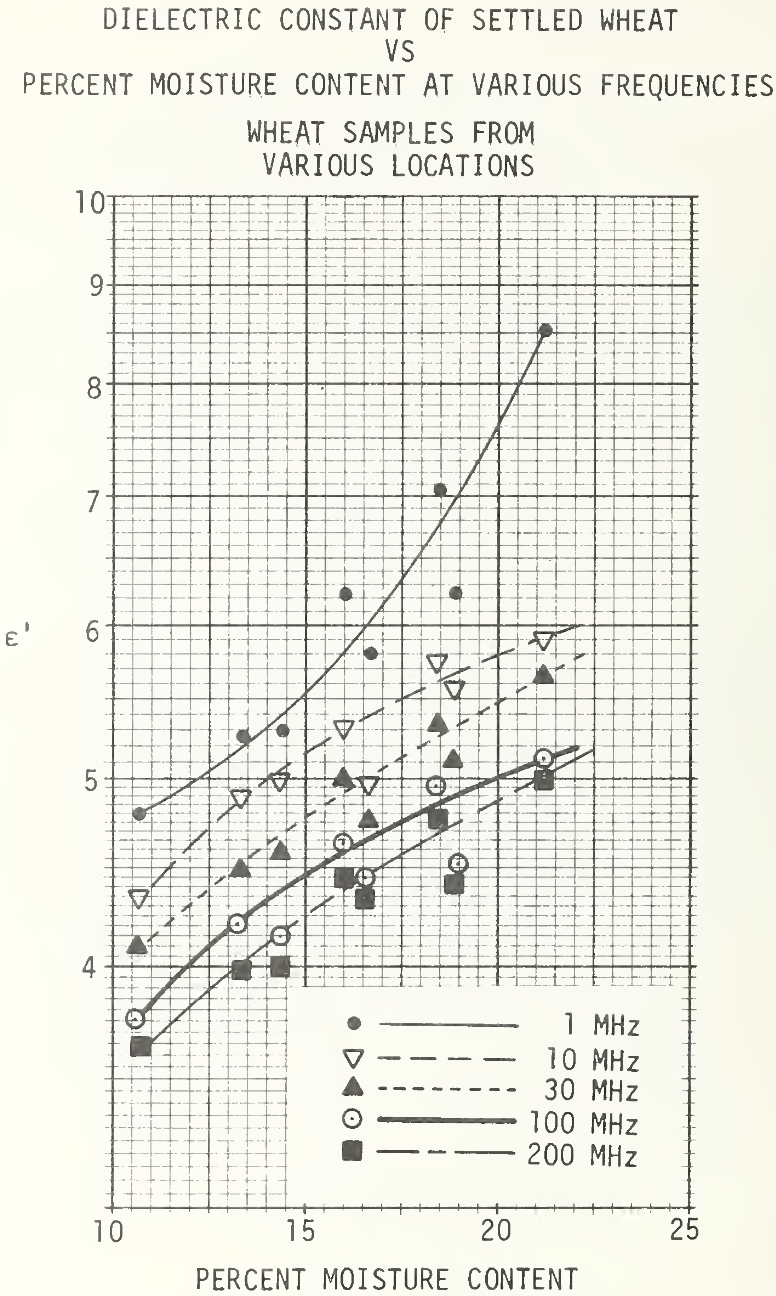

DIELECTRIC CONSTANT OF SETTLED WHEAT
VS
PERCENT MOISTURE CONTENT AT VARIOUS FREQUENCIES
WHEAT SAMPLES FROM
VARIOUS LOCATIONS
ε'
10
9
8
7
6
5
4
1 MHz
10 MHz
30 MHz
100 MHz
200 MHz
10
15
20
25
PERCENT MOISTURE CONTENT

Figure 10.

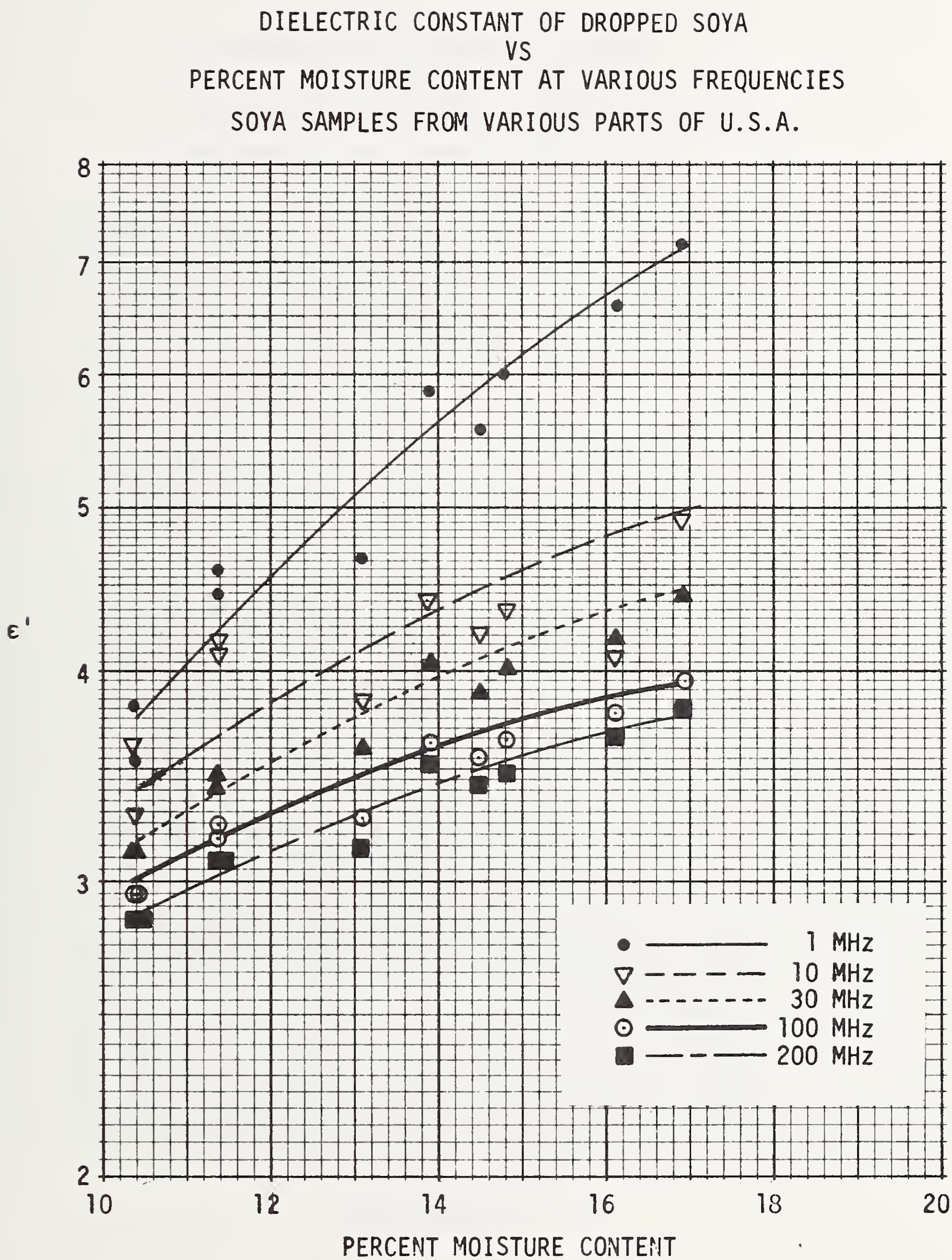

DIELECTRIC CONSTANT OF DROPPED SOYA
VS
PERCENT MOISTURE CONTENT AT VARIOUS FREQUENCIES
SOYA SAMPLES FROM VARIOUS PARTS OF U.S.A.
ε'
8
7
6
5
4
3
2
10
12
14
16
18
20
PERCENT MOISTURE CONTENT
1 MHz
10 MHz
30 MHz
100 MHz
200 MHz

Figure 11.

DIELECTRIC CONSTANT OF SETTLED SOYA
VS
PERCENT MOISTURE CONTENT AT VARIOUS FREQUENCIES

SOYA SAMPLES FROM VARIOUS LOCATIONS

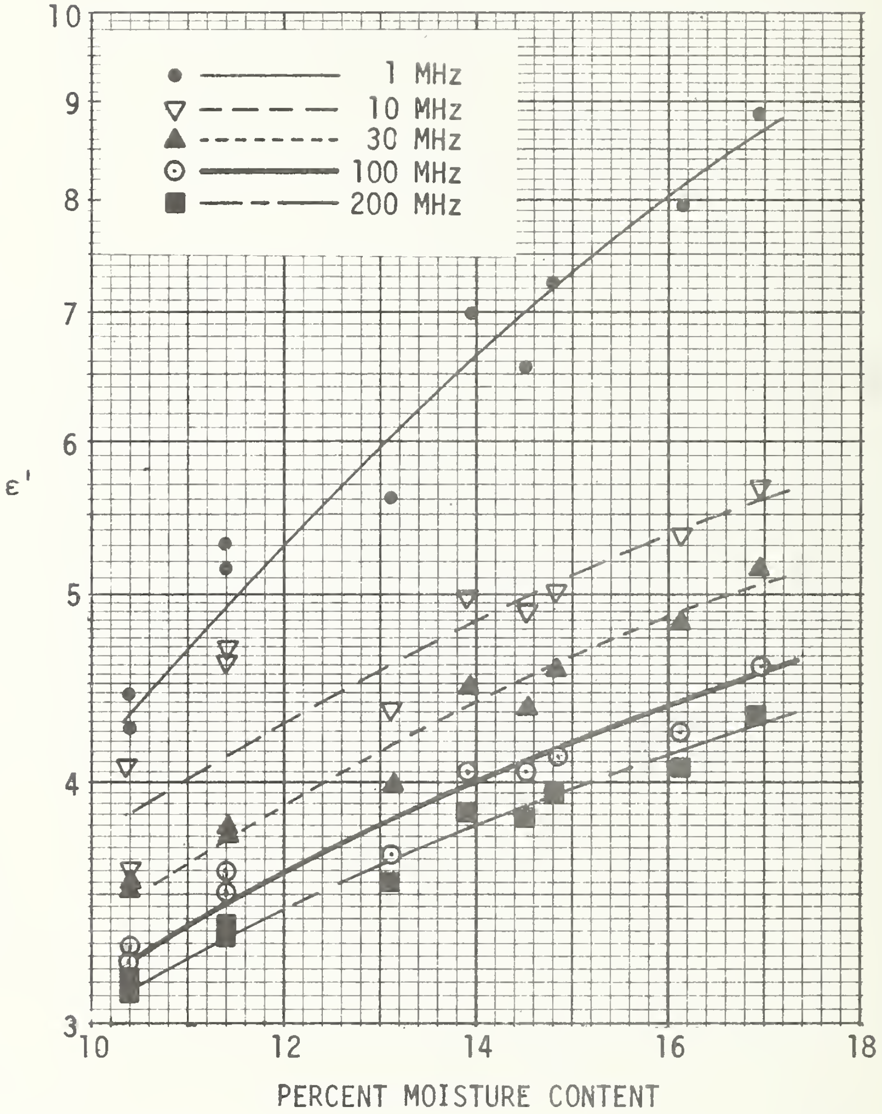


Figure 12.

LOSS TANGENT OF DROPPED CORN
VS
PERCENT MOISTURE CONTENT AT VARIOUS FREQUENCIES

CORN SAMPLES FROM JOE SMITH FARM NIWOT, COLO. NOV. 1976

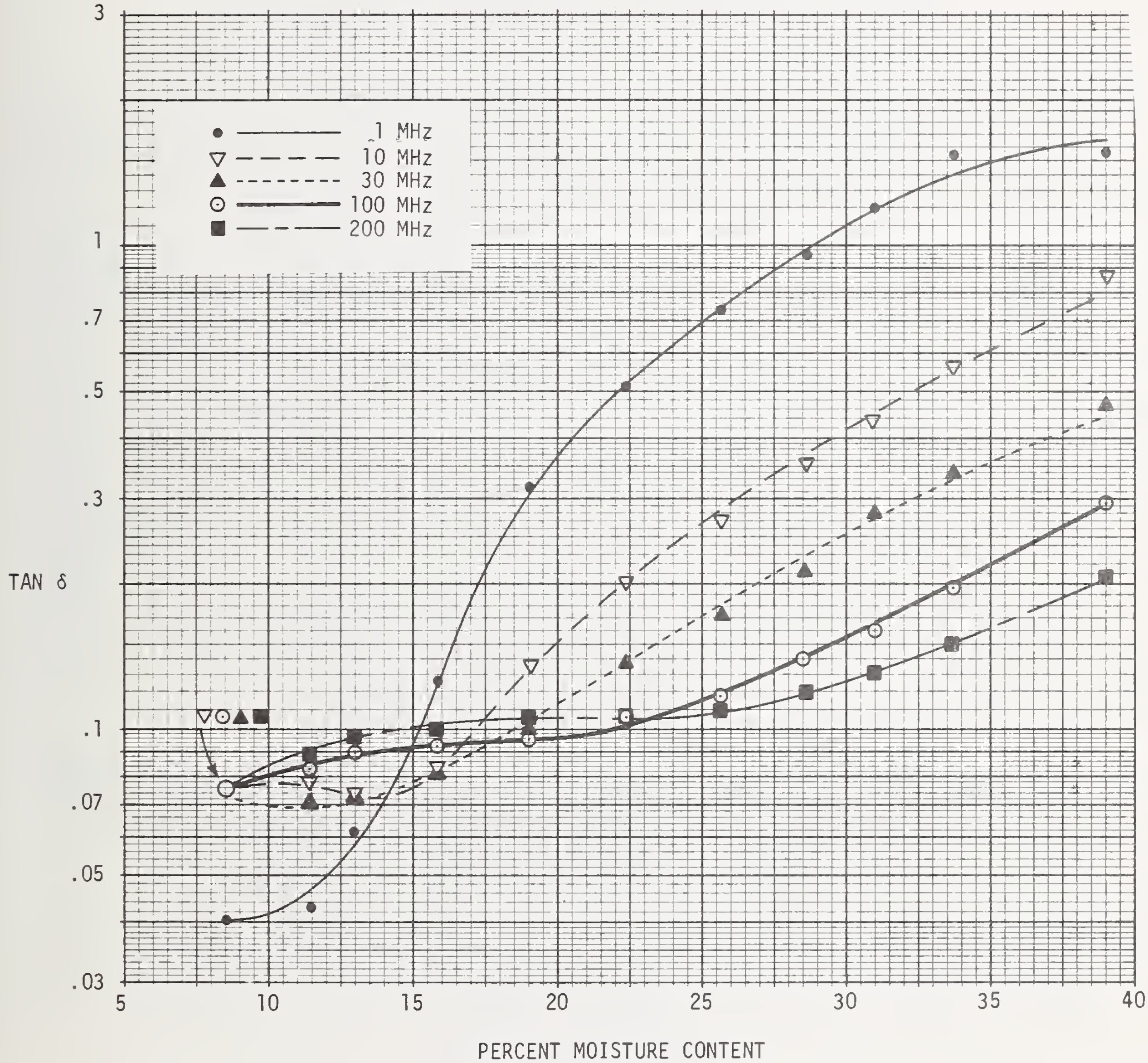


Figure 13.

LOSS TANGENT OF SETTLED CORN
VS
PERCENT MOISTURE CONTENT AT VARIOUS FREQUENCIES
CORN SAMPLES FROM JOE SMITH FARM, NIWOT, COLO. NOV. 1976

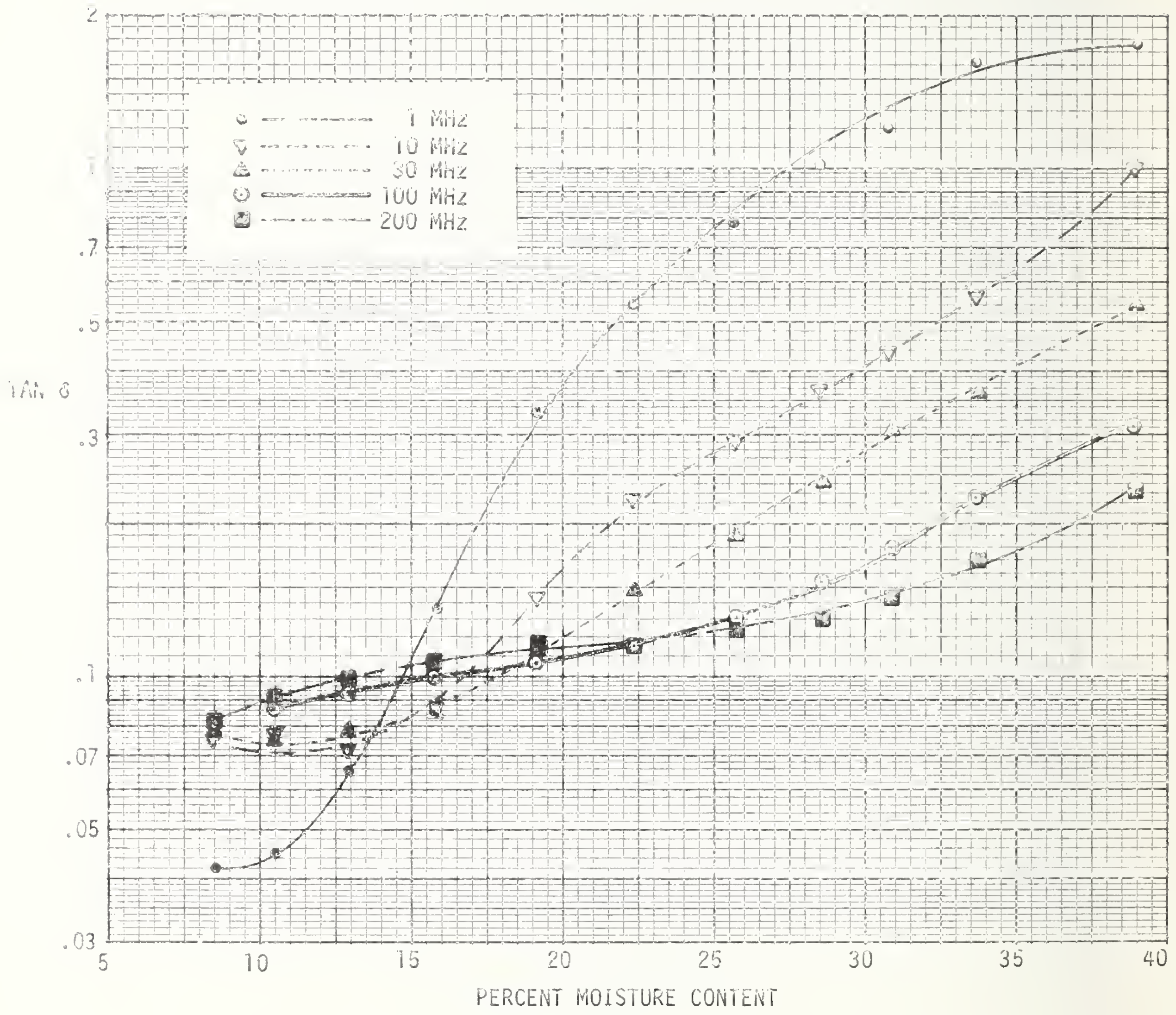


Figure 14.

LOSS TANGENT OF DROPPED CORN

VS

PERCENT MOISTURE CONTENT AT VARIOUS FREQUENCIES

CORN SAMPLES FROM MISCELLANEOUS LOCATIONS IN U.S.A.

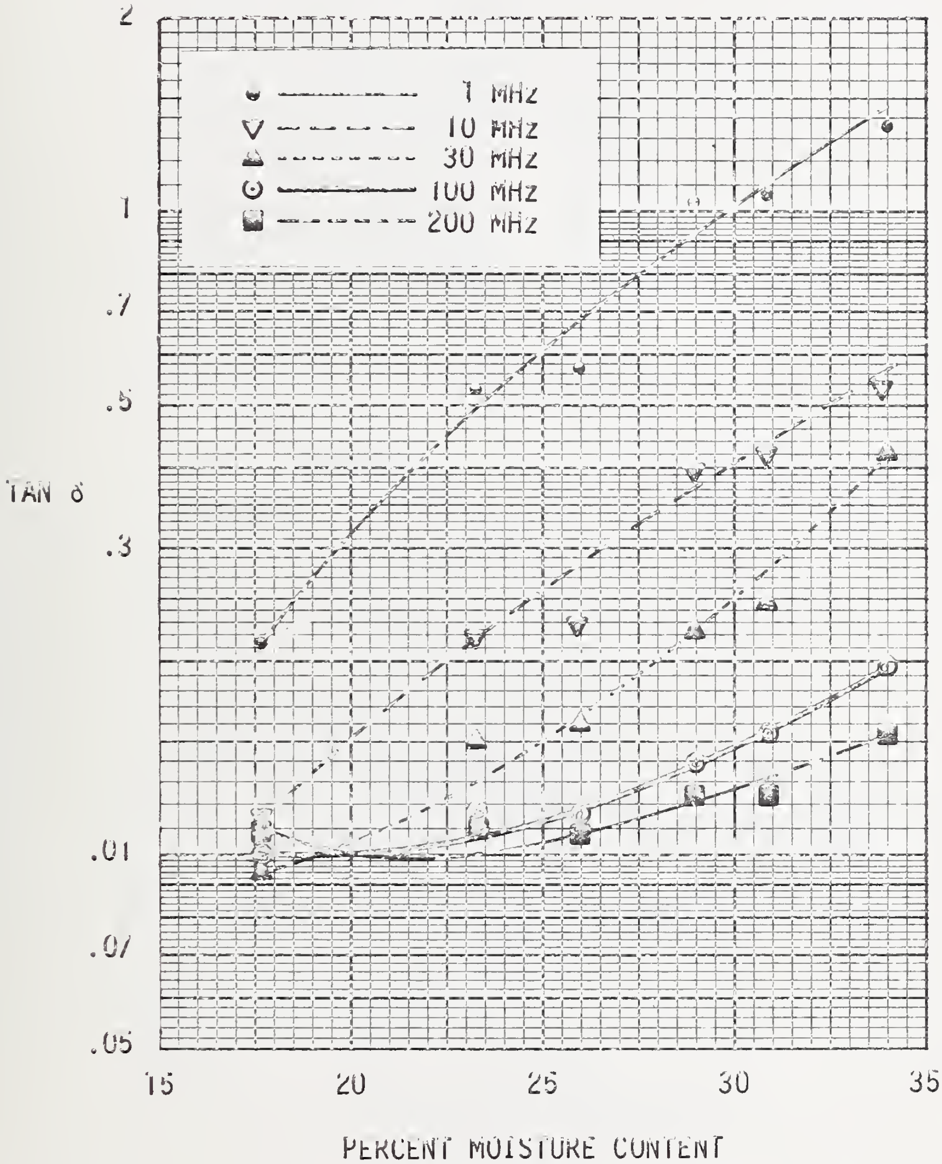
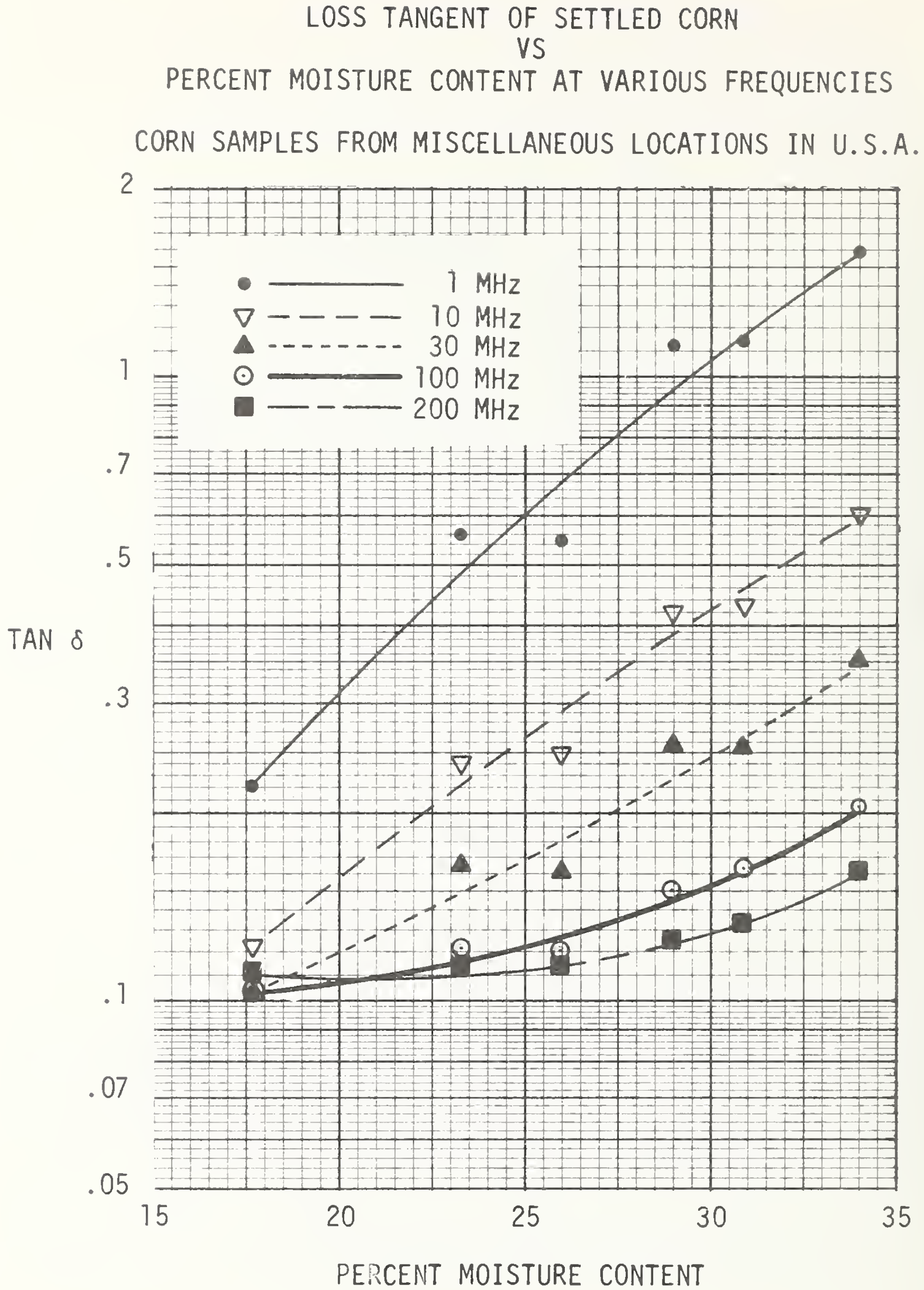


Figure 15.



LOSS TANGENT OF SETTLED CORN
VS
PERCENT MOISTURE CONTENT AT VARIOUS FREQUENCIES
CORN SAMPLES FROM MISCELLANEOUS LOCATIONS IN U.S.A.
1 MHz
10 MHz
30 MHz
100 MHz
200 MHz
TAN δ
2
1
.7
.5
.3
.1
.07
.05
15
20
25
30
35
PERCENT MOISTURE CONTENT

Figure 16.

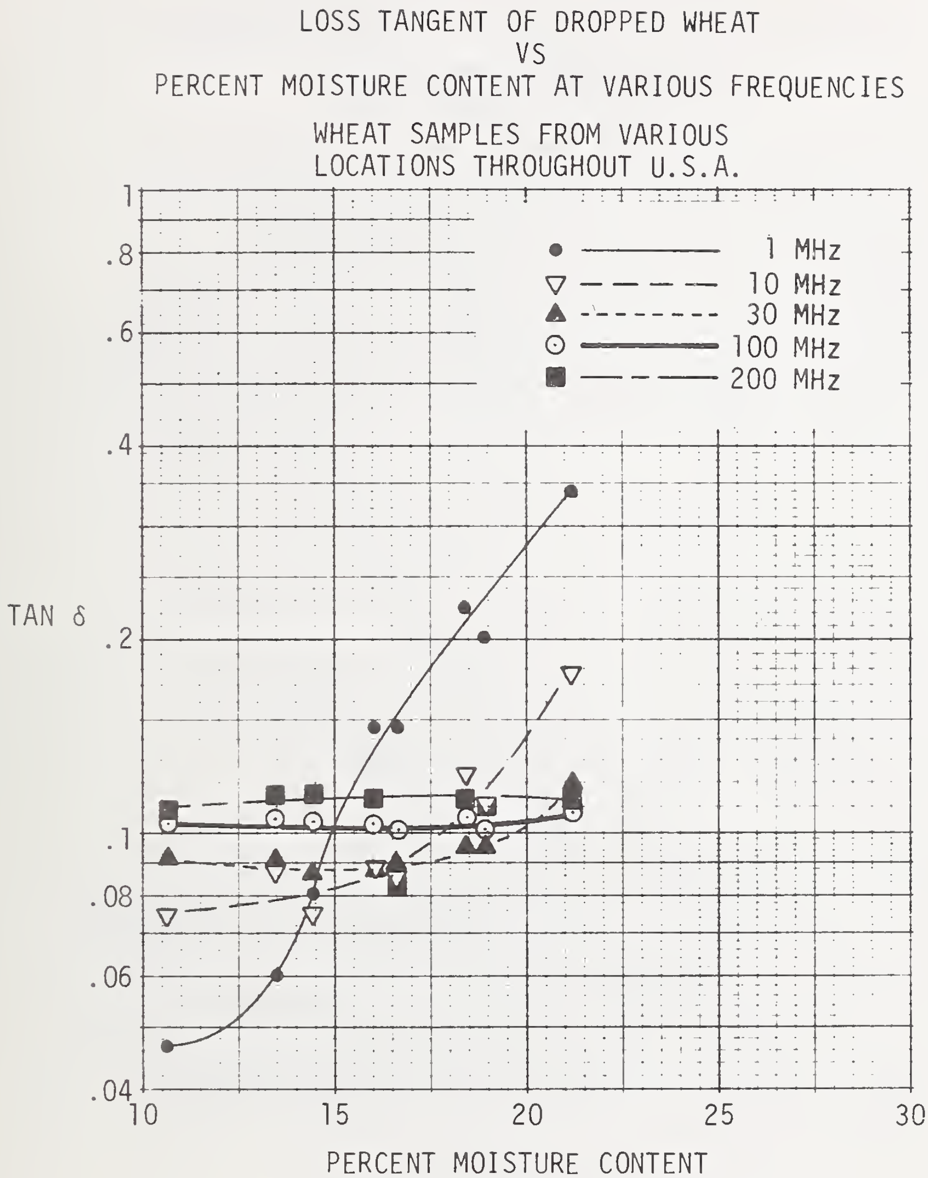

LOSS TANGENT OF DROPPED WHEAT
VS
PERCENT MOISTURE CONTENT AT VARIOUS FREQUENCIES
WHEAT SAMPLES FROM VARIOUS
LOCATIONS THROUGHOUT U.S.A.
1 MHz
10 MHz
30 MHz
100 MHz
200 MHz
TAN δ
1
.8
.6
.4
.2
.1
.08
.06
.04
10
15
20
25
30
PERCENT MOISTURE CONTENT

Figure 17.

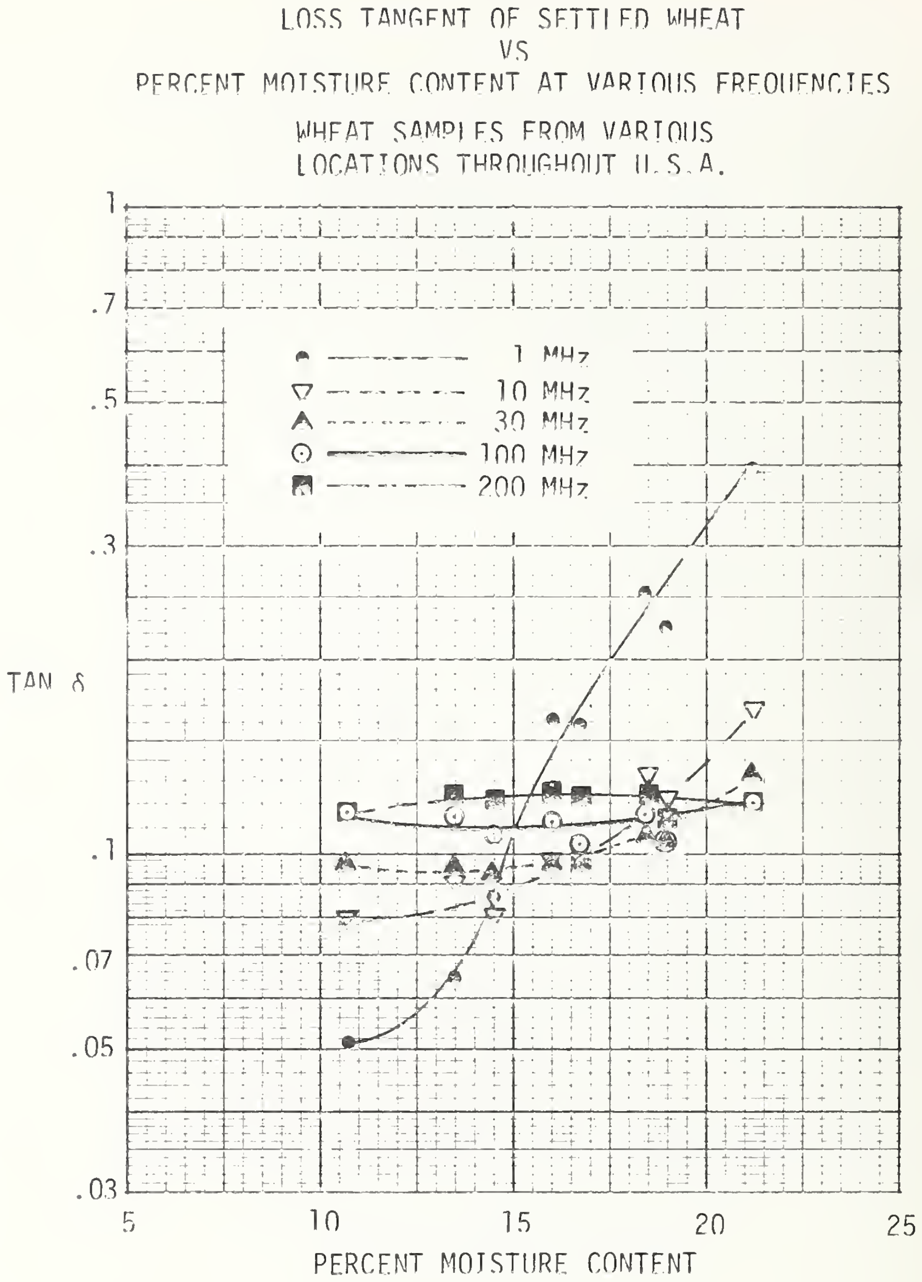

LOSS TANGENT OF SETTLED WHEAT
VS
PERCENT MOISTURE CONTENT AT VARIOUS FREQUENCIES
WHEAT SAMPLES FROM VARIOUS
LOCATIONS THROUGHOUT U.S.A.
1 MHz
10 MHz
30 MHz
100 MHz
200 MHz
TAN δ
1
.7
.5
.3
.1
.07
.05
.03
5
10
15
20
25
PERCENT MOISTURE CONTENT

Figure 18.

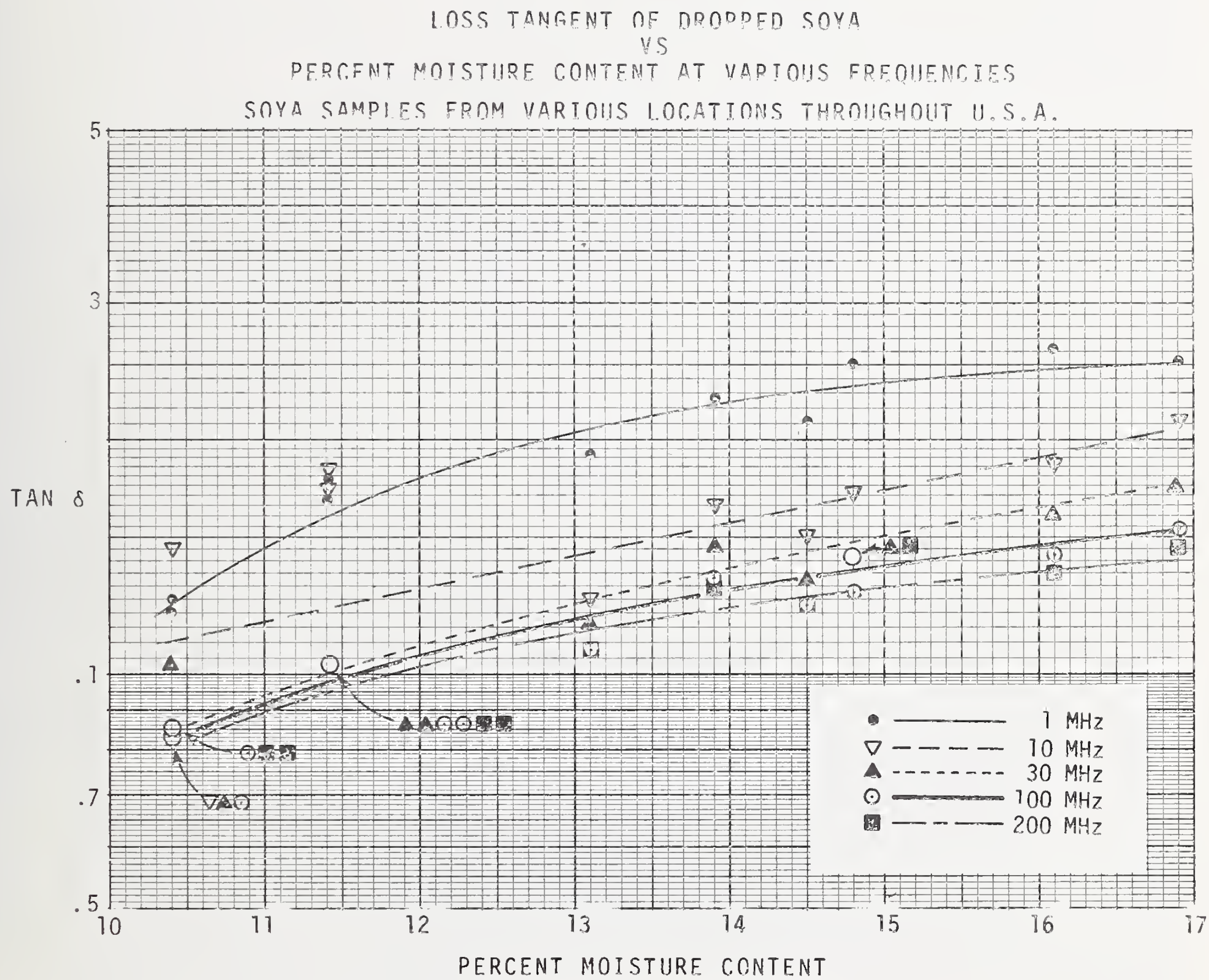

LOSS TANGENT OF DROPPED SOYA
VS
PERCENT MOISTURE CONTENT AT VARIOUS FREQUENCIES
SOYA SAMPLES FROM VARIOUS LOCATIONS THROUGHOUT U.S.A.
TAN δ
5
3
.1
.7
.5
10
11
12
13
14
15
16
17
PERCENT MOISTURE CONTENT
1 MHz
10 MHz
30 MHz
100 MHz
200 MHz

Figure 19.

LOSS TANGENT OF SETTLED SOYA
VS
PERCENT MOISTURE CONTENT AT VARIOUS FREQUENCIES
SOYA SAMPLES FROM VARIOUS LOCATIONS THROUGHOUT U.S.A.

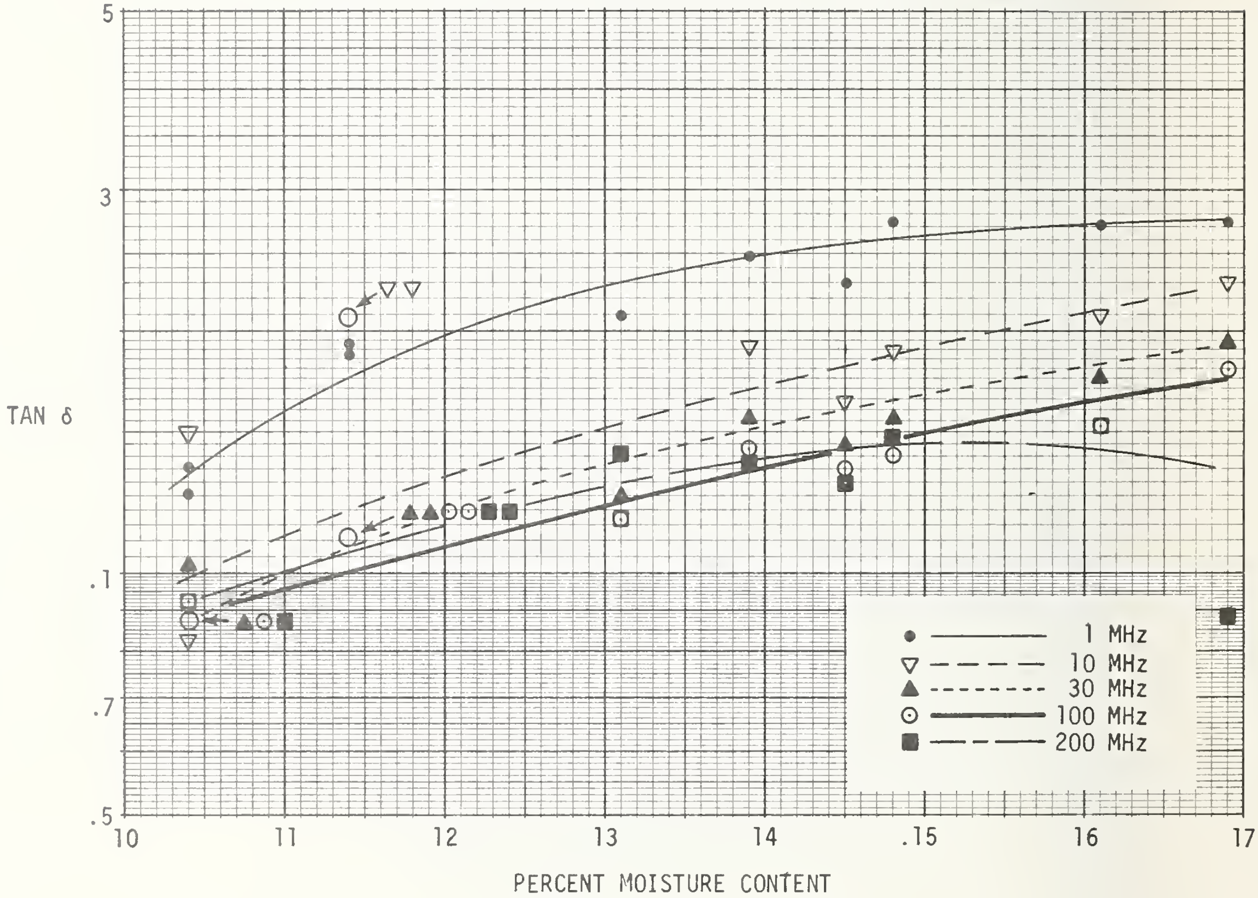


Figure 20.

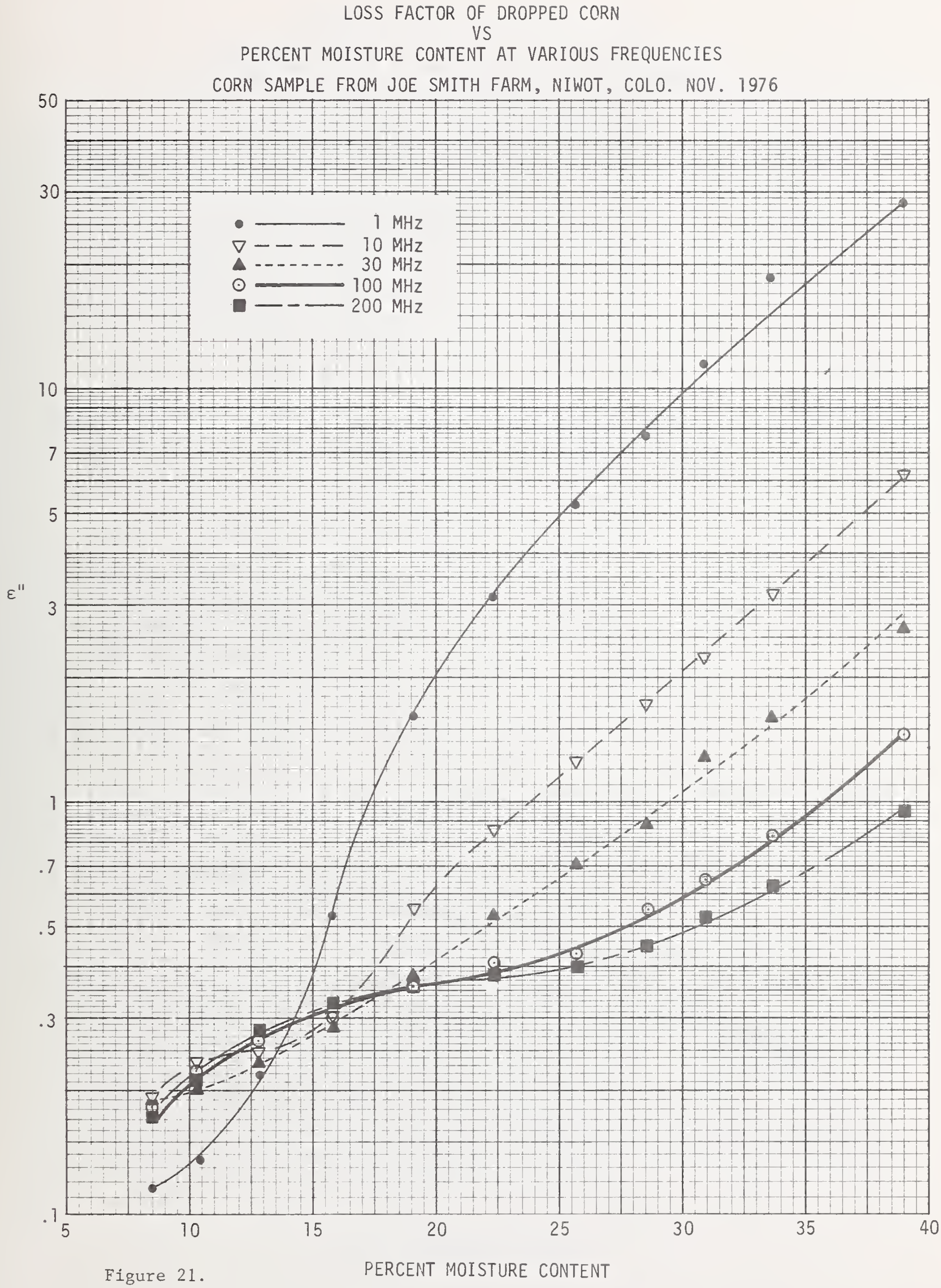

LOSS FACTOR OF DROPPED CORN
VS
PERCENT MOISTURE CONTENT AT VARIOUS FREQUENCIES
CORN SAMPLE FROM JOE SMITH FARM, NIWOT, COLO. NOV. 1976
1 MHz
10 MHz
30 MHz
100 MHz
200 MHz
ε"
50
30
10
7
5
3
1
.7
.5
.3
.1
5
10
15
20
25
30
35
40
PERCENT MOISTURE CONTENT

Figure 21.

LOSS FACTOR OF SETTLED CORN
VS
PERCENT MOISTURE CONTENT AT VARIOUS FREQUENCIES
CORN SAMPLE FROM JOE SMITH FARM, NIWOT, COLO. NOV. 1976

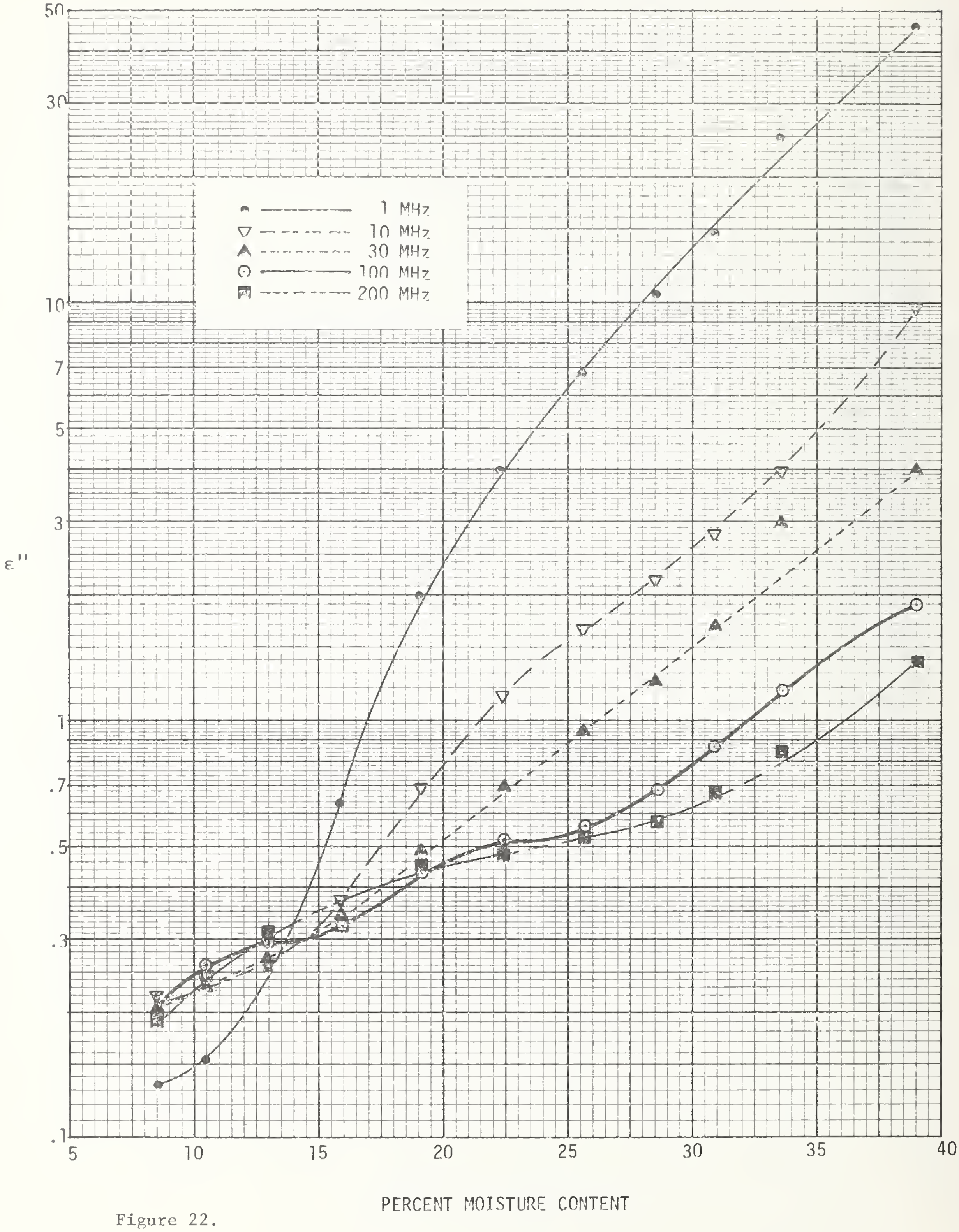


Figure 22.

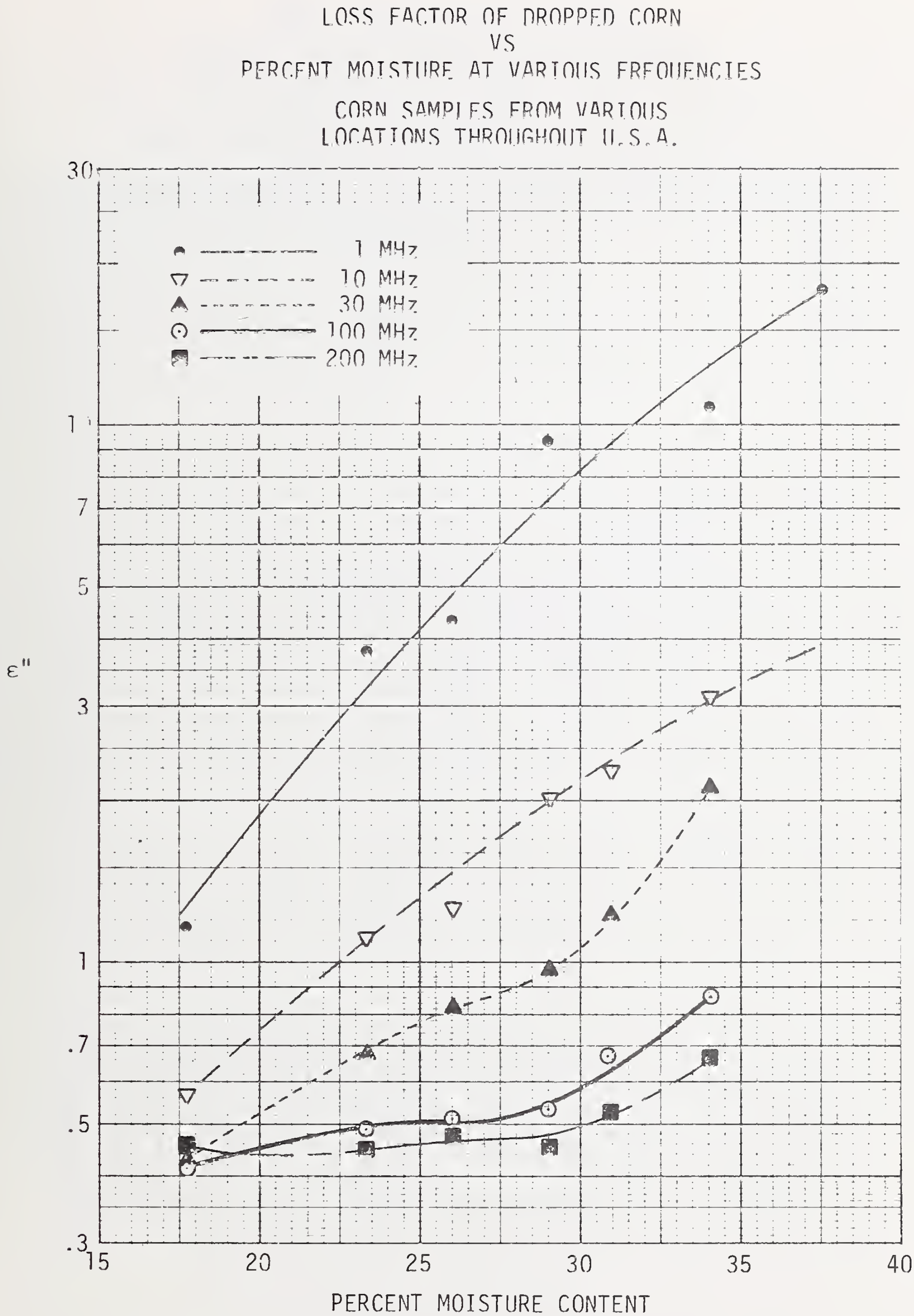

LOSS FACTOR OF DROPPED CORN
VS
PERCENT MOISTURE AT VARIOUS FREQUENCIES
CORN SAMPLES FROM VARIOUS
LOCATIONS THROUGHOUT U.S.A.
1 MHz
10 MHz
30 MHz
100 MHz
200 MHz
ε"
30
10
7
5
3
1
.7
.5
.3
15
20
25
30
35
40
PERCENT MOISTURE CONTENT

Figure 23.

LOSS FACTOR OF SETTLED CORN
VS
PERCENT MOISTURE AT VARIOUS FREQUENCIES

CORN SAMPLES FROM VARIOUS
LOCATIONS THROUGHOUT U.S.A.

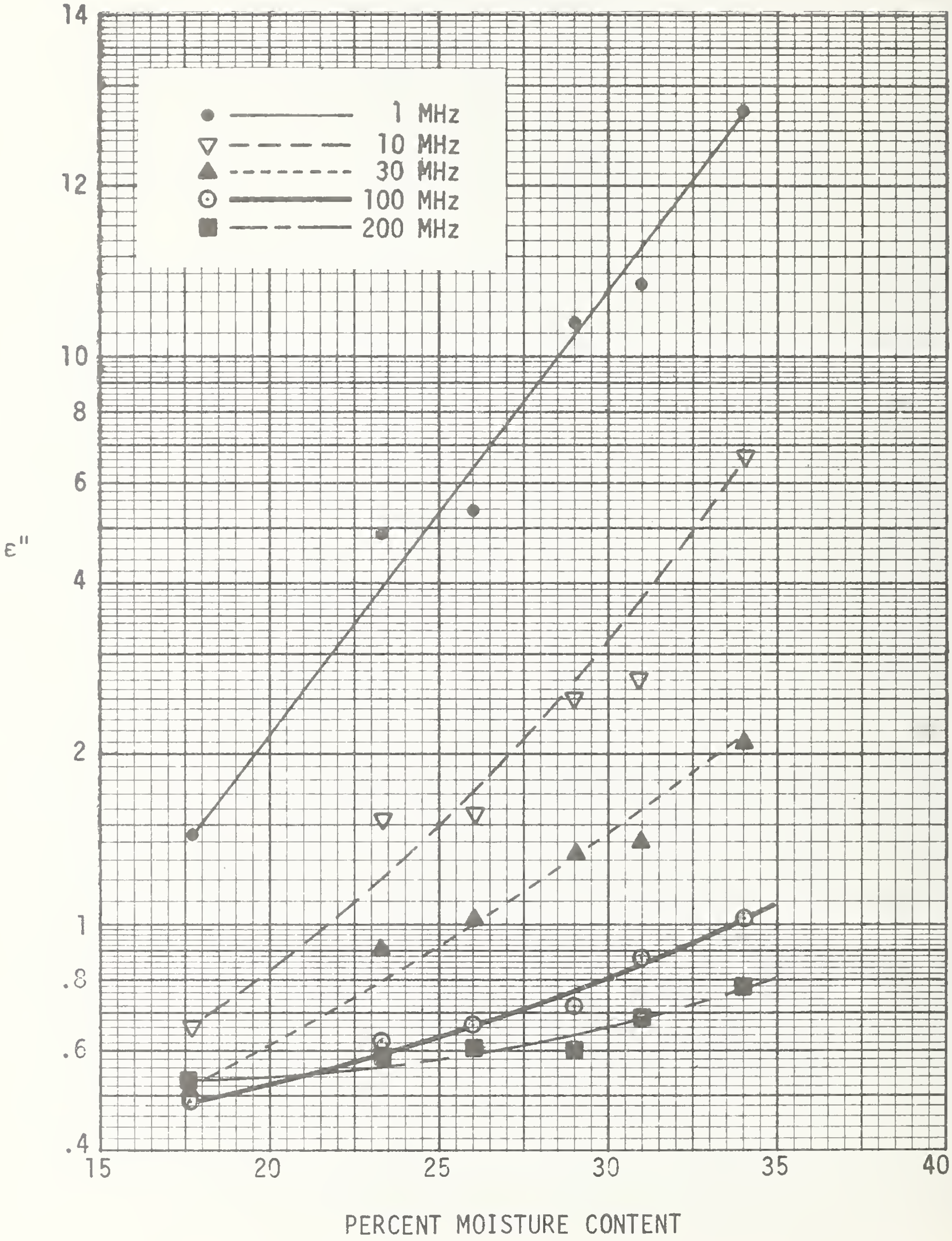


Figure 24.

LOSS FACTOR OF DROPPED WHEAT
VS
PERCENT MOISTURE CONTENT AT VARIOUS FREQUENCIES
WHEAT SAMPLES FROM VARIOUS LOCATIONS THROUGHOUT U.S.A

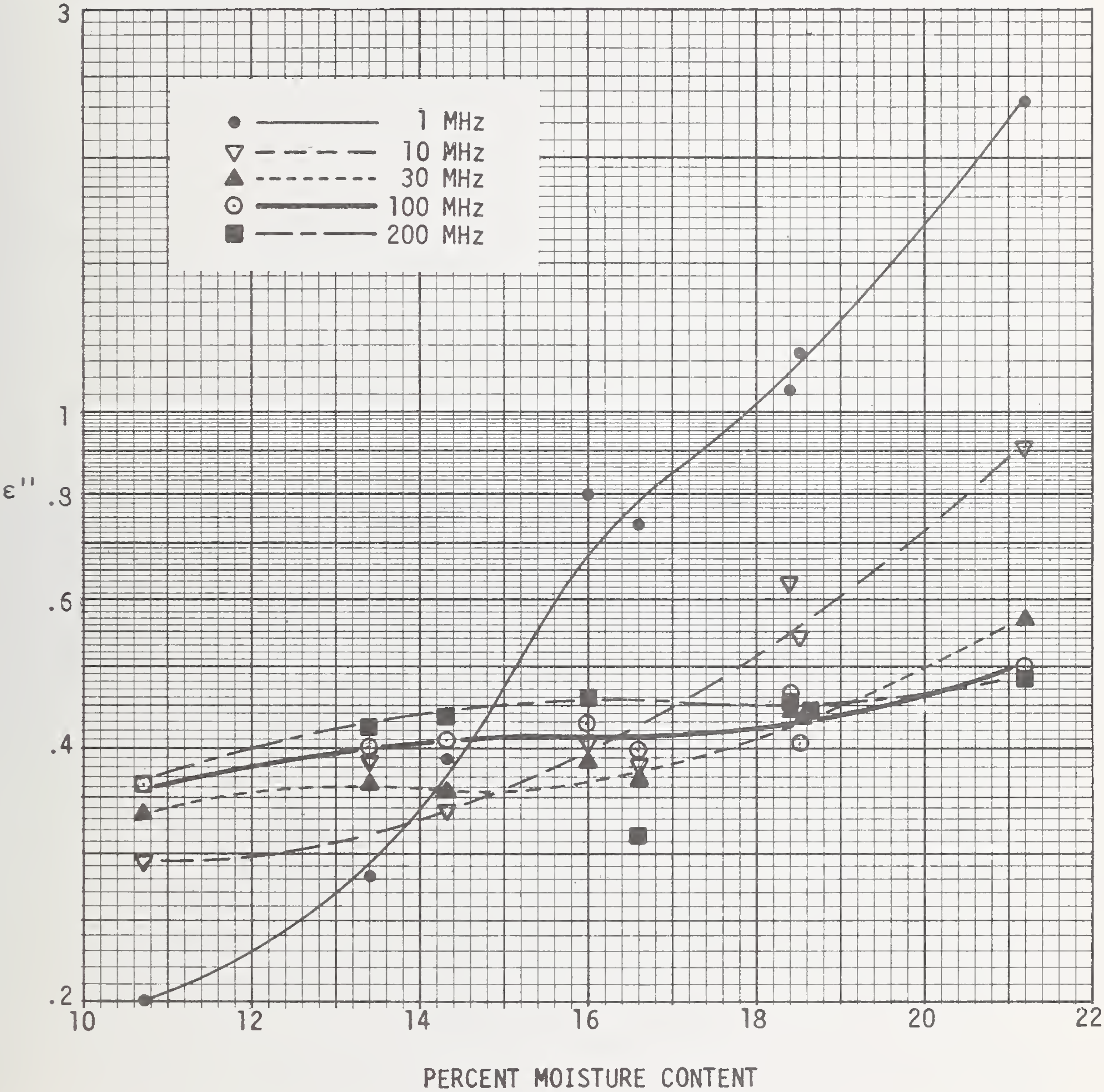


Figure 25.

LOSS FACTOR OF SETTLED WHEAT
VS
PERCENT MOISTURE CONTENT AT VARIOUS FREQUENCIES

WHEAT SAMPLES FROM VARIOUS LOCATIONS THROUGHOUT U.S.A.

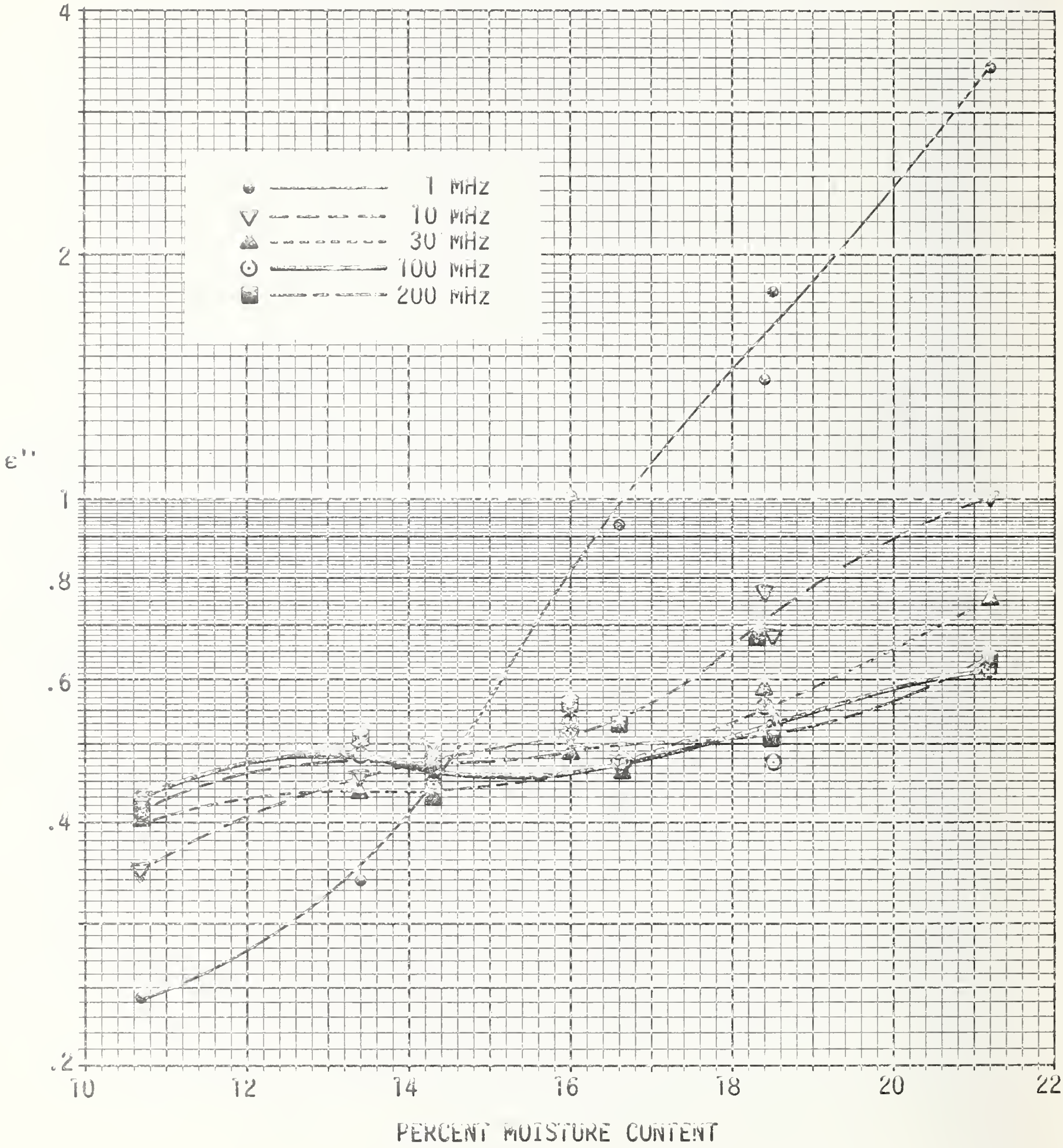


Figure 26.

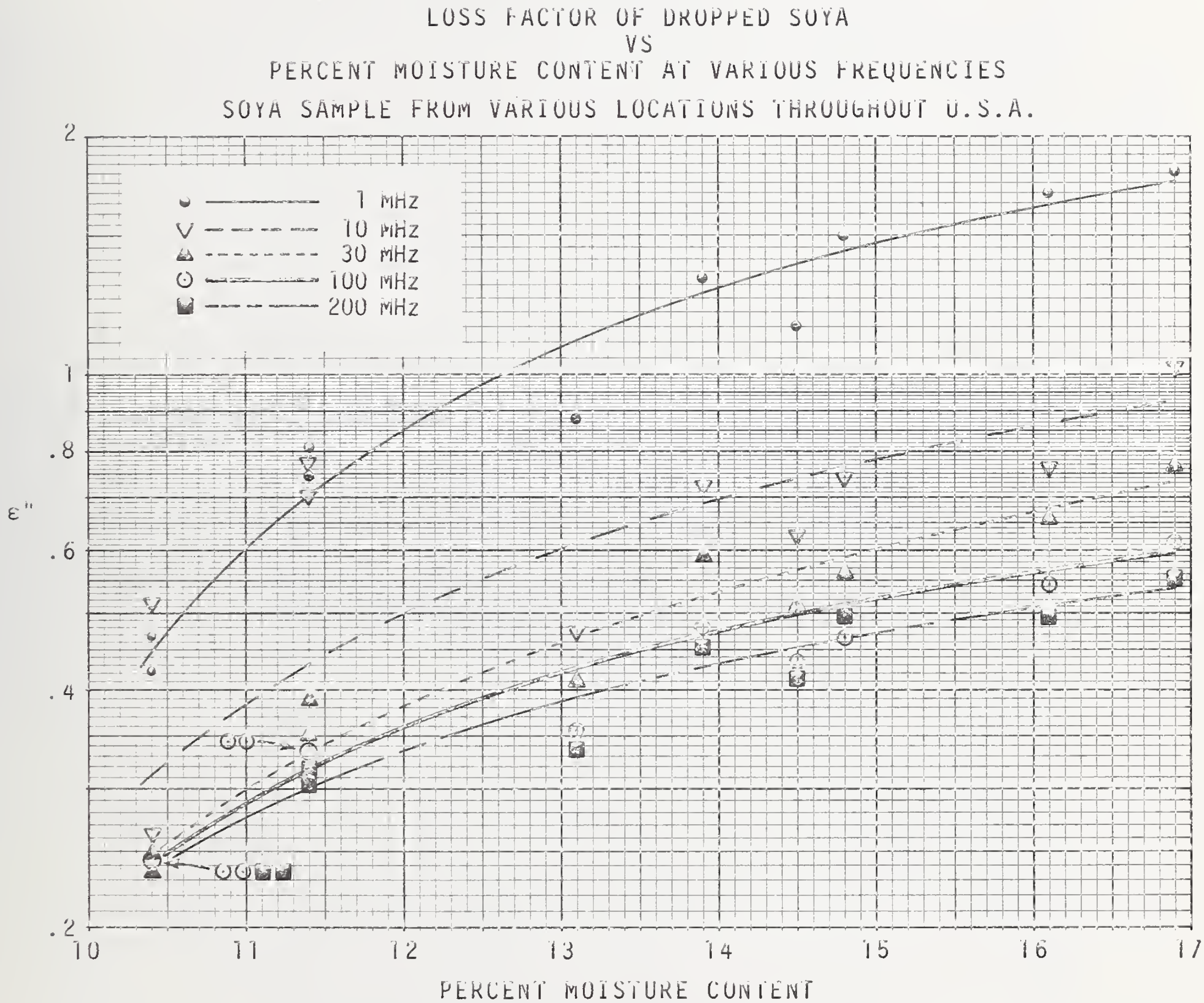
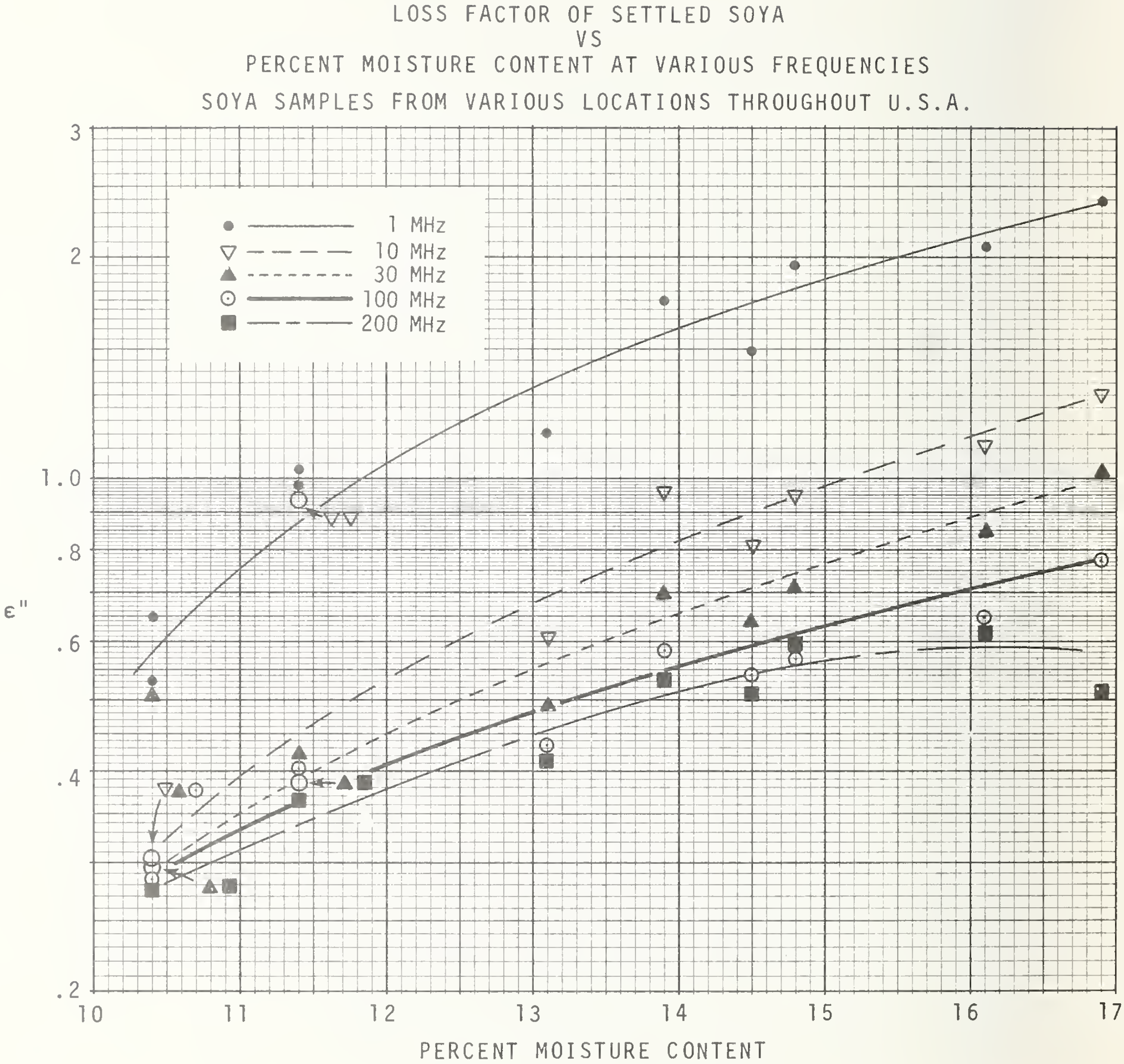

LOSS FACTOR OF DROPPED SOYA
VS
PERCENT MOISTURE CONTENT AT VARIOUS FREQUENCIES
SOYA SAMPLE FROM VARIOUS LOCATIONS THROUGHOUT U.S.A.
1 mHz
10 mHz
30 mHz
100 mHz
200 mHz
ε"
2
1
.8
.6
.4
.2
10
11
12
13
14
15
16
17
PERCENT MOISTURE CONTENT

Figure 27.



LOSS FACTOR OF SETTLED SOYA
VS
PERCENT MOISTURE CONTENT AT VARIOUS FREQUENCIES
SOYA SAMPLES FROM VARIOUS LOCATIONS THROUGHOUT U.S.A.
1 MHz
10 MHz
30 MHz
100 MHz
200 MHz
ε"
3
2
1.0
.8
.6
.4
.2
10
11
12
13
14
15
16
17
PERCENT MOISTURE CONTENT

Figure 28.

10.2 Density Versus Dielectric Constant

As mentioned earlier, a settling process was employed in the measurement procedure and data were gathered to indicate the dependence of the measured values of dielectric parameters upon the density or packing characteristics of the various grains. A summary of this data is provided in tables 11, 12, and 13.

Table 11. Ratio of settled to dropped parameters of various corn samples at 1 MHz.

Grain	Percent Moisture	Density Ratio	ε' Ratio	Tan δ Ratio	ε'' Ratio
Corn	17.7	1.04	1.16	1.08	1.25
Corn	23.3	1.12	1.23	1.06	1.31
Corn	26.0	1.11	1.28	0.97	1.25
Corn	29.0	1.12	1.16	1.08	1.26
Corn	30.9	1.13	1.25	1.09	1.36
Corn	8.5	1.05	1.07	1.06	1.13
Corn	10.4	1.02	1.07	1.05	1.13
Corn	12.9	1.06	1.10	1.07	1.17
Corn	15.8	1.08	1.12	1.08	1.21
Corn	19.1	1.09	1.16	1.06	1.23
Corn	22.4	1.11	1.19	1.04	1.25
Corn	25.7	1.13	1.20	1.06	1.27
Corn	28.6	1.10	1.25	1.07	1.33
Corn	30.9	1.11	1.23	1.00	1.23
Corn	33.7	1.12	1.27	1.05	1.34
Corn	39.0	1.13	1.44	1.13	1.62

Table 12. Ratio of settled to dropped parameters of various wheat samples at 1 MHz.

Grain	Percent Moisture	Density Ratio	ε' Ratio	Tan δ Ratio	ε'' Ratio
Wheat	10.7	1.08	1.12	1.09	1.21
Wheat	13.4	1.05	1.13	1.07	1.20
Wheat	14.3	1.06	1.09	1.07	1.16
Wheat	16.0	1.06	1.15	1.10	1.26
Wheat	16.6	1.09	1.15	1.09	1.26
Wheat	18.4	1.11	1.13	1.10	1.24
Wheat	18.5	1.08	1.18	1.13	1.33
Wheat	21.2	1.12	1.27	1.16	1.47

Table 13.

Grain	Percent Moisture	Density Ratio	ε' Ratio	Tan δ Ratio	ε'' Ratio
Soya	10.4	1.12	1.16	1.11	1.29
Soya	10.4	1.04	1.21	1.03	1.25
Soya	11.4	1.07	1.17	1.10	1.29
Soya	11.4	1.06	1.16	1.10	1.27
Soya	13.1	1.07	1.20	1.10	1.33
Soya	13.9	1.09	1.19	1.10	1.31
Soya	14.5	1.05	1.17	1.09	1.28
Soya	14.8	1.07	1.21	1.10	1.32
Soya	16.1	1.06	1.21	1.05	1.26
Soya	16.9	1.08	1.23	1.09	1.34

In tables 11-13 only the data from measurements at 1 MHz have been tabulated, and similar comparisons may be made at other frequencies by referring to the tabulation in the data section of this report. A few things seem immediately apparent from this data. Evidently the settling process produces the greatest change in the loss or conductivity portion of the complex dielectric constant since the ratios of settled to unsettled values are higher for ε'' than for ε'. This might allow ε'' to be used as a packing denisty indicator, which could in turn be used to correct ε' for the density effect. Regarding ε', it appears that the higher moisture levels of all three materials are more subject to packing density variations than the low moisture levels. This effect is most noticeable in the second corn sample in table 11, because of the wider moisture range (8.5 to 39 percent). However, over similar moisture ranges, the effect is about the same for the three materials tested.

10.3 Temperature Coefficient of ε' and Tan δ

A few experiments were performed on corn, wheat, and soya to determine the temperature coefficient of the dielectric parameters over the approximate range from 4 to 38°C. Samples of each of these materials having different moisture contents were tested, and moisture meter measurements were made before and after the tests to assure that significant changes in percentage moisture content had not occurred. The following tables 14, 15, and 16 provide a summary of the test results. Most of the data taken were at 30 MHz. The results are similar for wheat and soya. There was not adequate opportunity to work extensively enough with corn, and therefore the data are minimal. However, the tentative results do suggest that the temperature coefficient for both ε' and tan δ is larger at lower frequencies. This is a topic needing more investigation for a wider variety of frequencies and more samples of different moisture content. The technique used in these measurements was to begin with the grain sample either at the low or the high temperature, and allow it to simply warm or cool to room temperature. For each measurement the grain was transferred back and forth between the storage container and the dielectric sample holder, so that essentially the sample holder was kept near room temperature at all times during the test. As might be expected, the grain temperature changes fairly rapidly at the beginning of a test when the temperature difference between the sample and the laboratory environment is large. The later stages of a run proceed slowly, however; and as many as three hours were required for the sample to finally reach laboratory ambience. A possible source of error in determining temperature coefficient in the region below room temperature is condensation of moisture onto the grain from the surrounding air. Because additional moisture would tend to raise the dielectric constant, it follows that the temperature coefficient determined in this manner would be larger than that observed in the range above room temperature if such errors were present. This did not appear to happen for ε' of wheat and soya as tables 14 and 16 show.

Table 14. Wheat measurement.

Moisture Content %	Measurement Frequency MHz	Temperature Coefficient Units/°C ε'	Temp range(°C)	tan δ	Temp range(°C)
13.4	30	+ 0.020	4.5°C to 37°C	- 0.0005	
16.0	30	+ 0.022	6.4°C to 40°C	+ 0.0003	4°C to 22.5°C
				+ 0.0015	22.5°C to 40°C
18.4	30	+ 0.022	5.2°C to 40°C	- 0.0003	5°C to 23°C
				+.0047	23°C to 36°C
21.2	30	+ 0.019	3.2°C to 36.7°C	+ 0.0012	7°C to 34°C

Table 15. Corn measurement.

Moisture Content %	Measurement Frequency MHz	Temperature Coefficient Units/°C ε'	Temp range(°C)	tan δ	Temp range(°C)
34.6	1	(+)0.15	7 to 22	(+)0.02	7 to 22
34.6	30	(+)0.0003	7 to 22	(+)0.004	7 to 22

Table 16. Soya measurement.

Moisture Content %	Measurement Frequency MHz	Temperature Coefficient Units/°C ε'	Temp range(°C)	tan δ	Temp range(°C)
10.4	30	+ 0.028	25.5°C to 40°C	+ 0.0015	25.5°C to 40°C
11.4	30	+ 0.028	2°C to 22°C	+ 0.0011	2°C to 22°C
13.9	30	+ 0.028	25°C to 36°C	+ 0.0015	25°C to 36°C
16.1	30	+ 0.034	2°C to 22°C	+ 0.0022	2°C to 22°C

10.4 Effect of Sample Holder Size and Kernel Dimensions

Using the three sample holders described in table 1, a series of measurements was made to determine what effect the ratio of sample holder size to kernel size would have on measured ε', and tan δ. The grain samples included wheat (16.6% moisture content), corn (12.7% moisture content), and soya (9.8% moisture content). Data were obtained by dropping the samples into the holder with no settling procedure employed. Each sample was dropped ten times. Table 17 shows the average values for ε' and tan δ together with the standard deviations. Also shown in the table is the A/K ratio. A is the annular distance in the holder between the outer surface of the center conductor, and the inner surface of the outer conductor. K is an average "diameter" dimension for a typical kernel of wheat, corn, or soya. In the case of wheat and soya, K is the average of two measurements (largest and smallest) of a seed; and, in the case of corn, it was taken as the average of three measurements (length, width, and thickness). These values of K were used to represent an average dimension that could be used to compare with the sample holder dimension, recognizing that the kernels of the various materials will be in random orientations when dropped into the holder.

These observations indicate a definite relationship between holder diameter and the A/K ratio, and percentage differences for both ε' and tan δ are greater between the 2" and 3" holders than between the 3" and 4" holders (see table 18). The percentage change is similar for ε' and tan δ, but it appears to be more pronounced in the ε' values for corn. This is perhaps related to the larger kernel size compared to wheat or soy beans.

From this brief experiment we see that there is a systematic variation in measured values for ε' and tan δ which depends on the ratio of sample holder diameter to kernel size. We hypothesize that the measured effect is due to the packing geometry near the metallic walls. The dielectric values should approach an upper bound asymptotically as A/K increases. The fact that the apparent dielectric constant varies with A/K does not necessarily lead to a required diameter of the holder; but, when tables of moisture correlated to apparent dielectric constant are constructed, the holder diameter should be specified or A/K must be uniformly large for independence of diameter.

Table 17. Effect of sample holder and kernel dimensions on observed values of ε' and tan δ at 30 MHz, and standard deviation of 10 drops.

Data taken August 18, 1976

Holder Diameter	A/K Ratio	Grain	ε'	$\sigma_{\varepsilon'}$	Parameter Tan δ	$\sigma_{\tan\delta}$
5.08cm(2")	3.3	Wheat(16.6%)	4.084	0.023	0.0884	0.0005
7.62cm(3")	5.0	Wheat(16.6%)	4.192	0.021	0.0903	0.0005
10.16cm(4")	6.7	Wheat(16.6%)	4.233	0.020	0.0915	0.0008
5.08cm(2")	2.1	Corn(12.7%	3.490	0.028	0.0781	0.0007
7.62cm(3")	3.1	Corn(12.7%)	3.573	0.038	0.0799	0.0007
10.16cm(4")	4.2	Corn(12.7%)	3.702	0.020	0.0815	0.0011
5.08cm(2")	2.8	Soya(9.8%)	2.820	0.026	0.0682	0.0008
7.62cm(3")	4.2	Soya(9.8%)	2.873	0.021	0.0693	0.0007
10.16cm(4")	5.6	Soya(9.8%)	2.913	0.017	0.0711	0.0004
Data taken September 30, 1976						
Sept. 30 data (anodized center conductor and larger sample size)						
5.08cm(2")	3.3	Wheat (≈16%)	4.034	0.011	0.0866	0.0008
7.62cm(3")	5.0	Wheat (≈16%)	4.150	0.018	0.0878	0.0010
10.16cm(4")	6.7	Wheat (≈16%)	4.214	0.021	0.0917	0.0018

Table 18. Variation of ε' and tan δ with sample holder size, based on results in table 17.

Holders Larger-Smaller	Grain	% Differences Between Holders at 30 MHz ε'	Tan δ
7.62cm-5.08cm (3" - 2")	Wheat	2.6	2.1
	Corn	2.4	2.3
	Soya	1.9	1.6
10.16cm - 7.62cm (4" - 3")	Wheat	1.0	1.3
	Corn	3.6	2.0
	Soya	1.4	2.6
10.16cm - 5.08cm (4" - 2")	Wheat	3.6	3.5
	Corn	6.0	4.4
	Soya	3.3	4.3

10.5 Sample Size (Fill Level in Holder)

Referring again to the lower portion of table 17, additional data, taken at a later date, are tabulated for the same wheat sample (≈16%) as was used for the earlier observations of 8/18/76. The 9/30/76 data were taken using a larger sample size, thus filling the holder to a greater depth, to determine if this would yield different values for ε and and tan δ. Had the earlier sample size not been adequate to completely fill the electric field region of the sample holder, larger values for ε' should have resulted. Because this was not the case (smaller values were observed because even in capped jars the grain dried out a little), it is concluded that the sample sizes were adequate to yield accurate values for ε'.

10.6 Contact Impedance

Also during the 9/30/76 observations an anodized center electrode was used in the 3" sample holder to test whether contact impedance with the grain significantly affected the measured dielectric values. Because the measured value of tan δ only dropped from 0.0903 to 0.0878 and the standard deviation in tan δ remained nearly unchanged, it is concluded that variation of contact impedance is not a problem up to this moisture level. However, more testing should be done to verify this at higher moisture levels.

10.7 Drop Test of Corn, Wheat, and Soya (Standard Deviation)

The data in table 17 also provide a means of estimating the standard deviation of moisture meter measurements. To use an example, take the ε' value for the 12.7 percent corn obtained using the 4" sample holder. The standard deviation of the ten drops was $\pm$ 0.02 in ε', or $\pm$ 0.5 percent. Referring to figure 6 and the percent moisture content versus ε' plot at 30 MHz, the resulting error in determining the moisture content would have been $\pm$ 1.7 percent. Similar evaluations can be derived from this data for the other materials and for other measurement frequencies and levels of moisture content.

10.8 Overburden Effect on ε' and Tan δ

During the process of taking data on ε^* versus percent moisture content of the various materials, it was noticed that some change occurred as a result of setting the depth gauge on top of the grain after it was dropped into the holder. Some further data were taken which appear to confirm that the value of ε' is affected by pressure on the sample. Using the 3" sample holder and a wheat sample of 16.6 percent moisture content, the following results were obtained as static weight was added to the surface of the grain:

Table 19.

Weight on Sample(grams)	ε'	Tan δ	Depth Guage Reading inches
0	4.1253	0.0880	
171.4	4.1406	0.0888	1.13
318.9	4.1544	0.0896	1.16
613.9	4.1884	0.0892	1.17
318.9	4.1866	0.0885	1.17
171.4	4.1875	0.0877	1.17
0	4.1864	0.0871	

Although there was practically no change in the depth gauge reading as a result of adding the weight, a noticeable increase occurred in the value observed for dielectric constant; but the change was not reversible upon removal of the weight as the table of data shows. Such an effect might be important in an in situ measurement where, because of overburden, grain moisture would artificially appear to increase at greater depths in a container.

10.9 Glass Bead Experiments

In order to gain some appreciation for the uniqueness of the dielectric behavior of grain as opposed to any other particulate matter, some experimentation was done using a sample of glass beads in the 2" sample holder. The beads were not uniform in shape or size although they were generally spherical having diameters averaging approximately 0.424 cm (0.167") and variations of the order of 0.025 cm ($\pm$ 0.01"). Dropping the sample of beads into the holder eleven times produced a value for ε' of 3.311 with a standard deviation, σ, of 0.017 and a value for tan δ of 0.0057 with σ of 0.0008. Thus the repeatability of the bead sample is comparable with the repeatability of the various samples of corn, wheat, and soya.

Considering the possibility that some stable particulate material such as glass beads could be useful as a standard for electric moisture meter calibration, some further experimentation was done to learn what effect settling would have on the value obtained for ε'. The sample was first dropped into the holder and values for ε' and tan δ observed, followed by remeasurement of ε' and tan δ after repeated settling.

	Sample Condition	ε'	tan δ	Density g/cc
	Dropped	3.315	0.0048	1.507
Repeated Settling	Settled	3.470	0.0045	1.577
	Settled	3.492	0.0062	1.591
	Settled	3.504	0.0050	1.591
	Settled	3.506	0.0047	1.591

After repeated settling the bead sample in the holder appeared to reach a limiting value for ε'. To see how reliable this limiting value might be, a different settling technique was used. Instead of dropping the entire charge of beads into the sample holder at one time and vibrating them afterward, the beads were poured into the holder in small increments with settling done between each increment. This produced the following result which can be compared to the previous data:

ε'	tan δ	Density g/cc
3.665	0.0057	1.618

Thus by settling the sample incrementally the value of ε' increased 10.5 percent compared to the original dropped value. Comparing the change of density to the change in ε' shows that a density change of 7.4 percent was accompanied by a 10.5 percent change in the observed value of ε'. This is shown in more detail by the graph in figure 29. After some initial settling the relationship between ε' and density appears to be linear as shown by the solid portion of the graph. The lower portion is shown as a broken line because of the absence of data points in this region.

To utilize some material such as glass beads as a standard for electric moisture meters would require careful research to determine such information as optimum bead material and size, required degree of uniformity of bead size and shape, and application techniques to be followed. Certainly any bead material selected would have to have an ε' value in the same range as grain. Such material in the form of beads is difficult to locate.

11. CONCLUSIONS

Based upon the data accumulated using the equipment and methods described in this report, the following conclusions have been reached:

1. In utilizing dielectric constant, ε', as an indicator of percent moisture content for the three materials tested, frequencies in the vicinity of 1 MHz or below provide greater sensitivity or measurement resolution than frequencies in the vicinity of 200 MHz. This is illustrated in figures 5 and 6 where the sensitivity is 0.6 ε' units per one percent change in moisture content at 1 MHz compared to 0.12 ε' units per one percent change in moisture content at 200 MHz.

2. The measured value of ε' is a function of the packing density of the sample of material in the holder. For measurement repeatability it is important that density be kept constant from one sample to another. From these experiments the dropping technique appeared to provide better density repeatability than the settling process devised for this experiment.

3. The measured value of ε' approaches a limiting maximum value as the density increases and also approaches a maximum value.

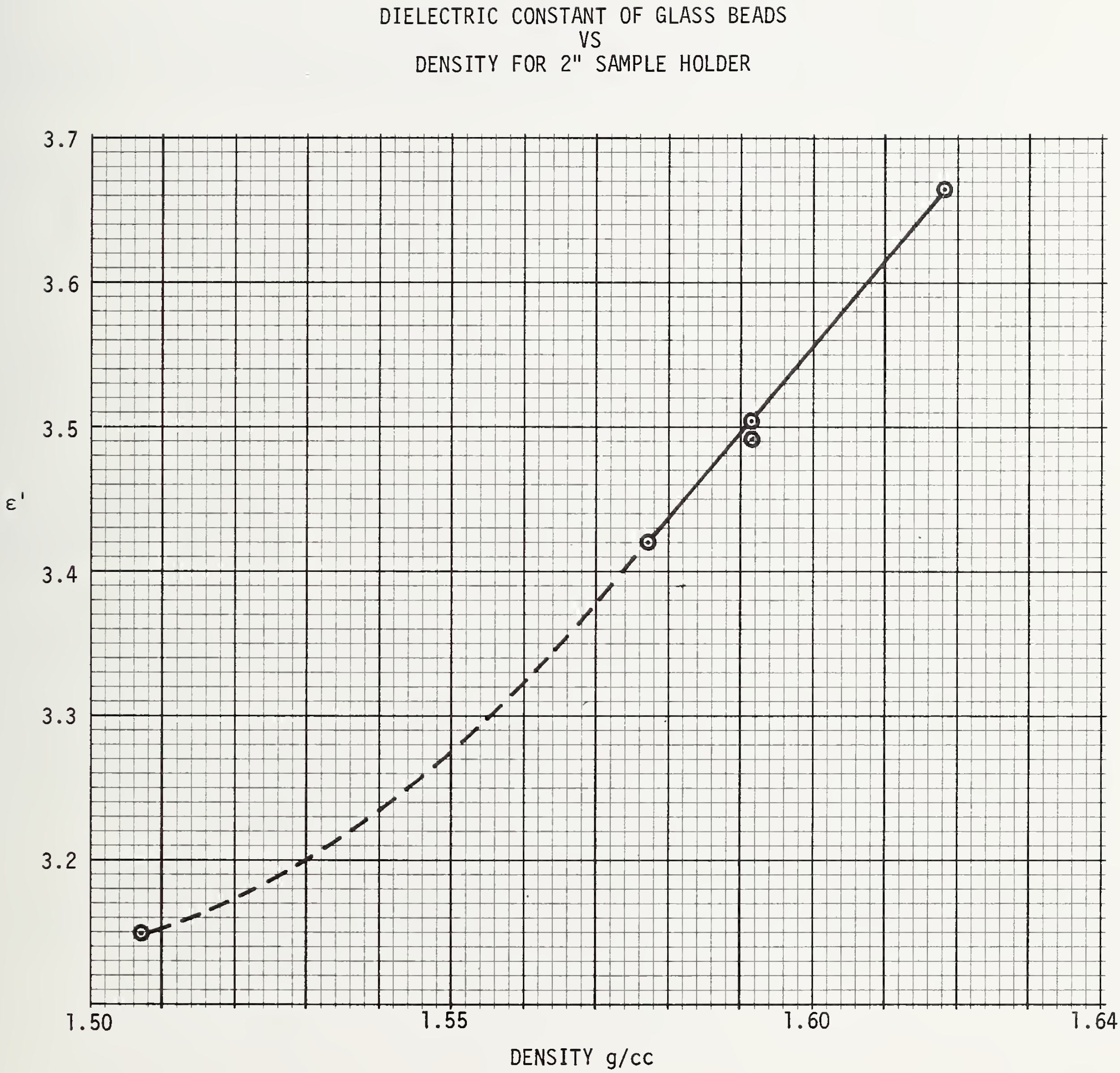

DIELECTRIC CONSTANT OF GLASS BEADS
VS
DENSITY FOR 2" SAMPLE HOLDER
3.7
3.6
3.5
3.4
3.3
3.2
ε'
1.50
1.55
1.60
1.64
DENSITY g/cc

Figure 29.

4. The ratio of sample holder diameter to kernel size has an apparent effect upon the observed value of dielectric constant up to an A/K ratio of approximately 5.

5. The sample volumes used in these experiments permitted the sample holder center conductor to be covered to a depth equal to about two center conductor diameters and were adequate to permit ε' measurement which was free from errors due to underfilling.

6. Adding an anodized coating to the center conductor of a sample holder produced no significant change in the measured value of complex dielectric constant for wheat at 16% moisture content.

7. The effect of temperature on the observed values for dielectric constant was small at frequencies of 1 and 30 MHz. Temperature coefficients of the order of $+ 0.02$ ε' units per degree centigrade and 0.01 tan δ units per degree centigrade were observed for wheat, corn, and soya over the range from 4 to 40 degrees centigrade.

8. An apparent increase in dielectric constant, ε', due to surface weight on the grain sample was observed. The addition of approximately 600 grams to the surface of the sample produced a change in dielectric constant change of + 1.5%. This change was not accompanied by a measurable change in tan δ, and only a very small change in density. Also the change in dielectric constant was not reversible upon removal of the weight.

9. The ε' versus percent moisture relationship at higher moisture levels (>25%) for corn was continuous with the data at levels below 25%, and did not pose a problem for the passive circuit equipment used. For meters utilizing an active oscillator circuit, the low Q values of a test cell when filled with high moisture grain could be a problem.

10. There is an apparent difference in the behavior of the dielectric parameters depending on growing conditions and hybrid seed type. This conclusion is weak, however, because of the doubt as to the accuracy of the moisture level percentages in the test samples.

Much of this work supports the practices in current use by the U.S.D.A. in its grain inspection procedures. Of specific note are the practice of dropping the sample into the holder, and the development of special calibration charts for particular geographic areas.

Areas of possible future interest not covered by this report include a study of the effects of other parameters on the accuracy of moisture measurement. Included among the other parameters are kernel shape, and the presence of other constitutents including protein, carbohydrate, fat, and fiber content, bound and unbound water, and possible changes due to enzymatic processes. Another approach might also be the study of dielectric constant as a function of the density of a single kernel as distinguished from bulk density.

It also appears desirable to extend the work to include measurments at frequencies below 1 MHz because the values for ε' are continuing to increase with decreasing frequency. This enhances the prospect for still higher resolution which is an important consideration in choosing the optimum measurement frequency.

12. ACKNOWLEDGMENT

We would especially like to thank Mr. Hayward Hunt and his staff at the U.S. Department of Agriculture Grain Standardization Laboratory in Beltsville, Maryland, for their support in providing grain samples to us which had been analyzed by their oven-dry facility. Also their cooperation and advice were very helpful.

It is appropriate to acknowledge the work of others whose labors have preceded ours in this subject area. Many have contributed, and a complete bibliography of their work would be a project in itself. However, because of the similarity of effort and the nearly common objectives, we would especially like to reference the work of those at the Agricultural Research Service of the U. S. Department of Agriculture at the University of Nebraska, specifically S. O. Nelson, R. E. Stetson, J. L. Jorgensen, and A. R. Edison [10,11]. In many respects our work has been similar, and their papers have been most valuable. A recent paper [12] by Nelson gives a good bibliography.

Also allow us to make special mention of two laboratory assistants whose work was so vital. Jocelyn Spencer and Douglas Tamura both put forth excellent work through some long and tedious hours.

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GRAIN	Percent Moisture	DENSITY grams/cubic cm. Dropped	DENSITY grams/cubic cm. Settled	Density Ratio Settled to Dropped	ϵ' Dropped	ϵ' Settled	$\tan\delta$ Dropped	$\tan\delta$ Settled	ϵ'' Dropped	ϵ'' Settled	Remarks
Corn	17.7	0.675	0.704	1.04	5.714	6.603	0.2055	0.2219	1.174	1.465	1 MHz Data
	23.3	0.607	0.680	1.12	7.162	8.824	0.5272	0.5608	3.776	4.948	of 11/1/76
	26.0	0.637	0.707	1.11	7.551	9.690	0.5709	0.5563	4.311	5.391	Samples from
	29.0	0.521	0.582	1.12	8.875	10.37	1.038	1.123	9.212	11.65	various parts
	30.9	0.514	0.580	1.13	9.498	11.83	1.061	1.157	10.08	13.69	of U.S.A.
	34.0	0.520	0.573	1.10	12.96	16.62	1.370	1.627	17.76	27.05	
Corn	8.5	0.609	0.640	1.05	2.911	3.107	0.0400	0.0424	0.1164	0.1317	
	10.4	0.617	0.631	1.02	3.135	3.357	0.0435	0.0458	0.1364	0.1538	
	12.9	0.608	0.646	1.06	3.573	3.924	0.0610	0.0650	0.2180	0.2551	1 MHz Data
	15.8	0.600	0.650	1.08	4.159	4.662	0.1267	0.1372	0.5269	0.6396	of 12/15/76
	19.1	0.586	0.637	1.09	5.139	5.949	0.3143	0.3323	1.615	1.979	All samples from
	22.4	0.559	0.619	1.11	6.134	7.329	0.5147	0.5364	3.157	3.931	same field. Air
	25.7	0.530	0.600	1.13	7.081	8.503	0.7399	0.7847	5.239	6.672	dried on cob from
	28.6	0.527	0.578	1.10	8.131	10.13	0.9594	1.024	7.801	10.38	39% to 8.5%
	30.9	0.510	0.566	1.11	9.794	12.03	1.200	1.200	11.75	14.44	
	33.7	0.508	0.568	1.12	12.02	15.30	1.537	1.616	18.48	24.73	
	39.0	0.509	0.575	1.13	18.32	26.30	1.540	1.742	28.22	45.83	

GRAIN	Percent Moisture	DENSITY grams/cubic cm. Dropped	DENSITY grams/cubic cm. Settled	Density Ratio Settled to Dropped	ε′ Dropped	ε′ Settled	tan δ Dropped	tan δ Settled	ε″ Dropped	ε″ Settled	Remarks
Wheat	10.7	0.826	0.889	1.08	4.316	4.815	0.0470	0.0510	0.2029	0.2455	
	13.4	0.811	0.851	1.05	4.689	5.281	0.0602	0.0642	0.2823	0.3391	1 MHz Data
	14.3	0.794	0.843	1.06	4.868	5.303	0.0800	0.0855	0.3894	0.4534	of 11/4/76
	16.0	0.782	0.832	1.06	5.420	6.223	0.1469	0.1613	0.7962	1.004	Samples from
	16.6	0.723	0.789	1.09	5.052	5.824	0.1462	0.1599	0.7387	0.9313	western Kansas
	18.4	0.735	0.814	1.11	5.541	6.273	0.2030	0.2226	1.125	1.396	and various other
	18.5	0.715	0.775	1.08	6.003	7.071	0.2266	0.2550	1.360	1.803	parts of U.S.A.
	21.2	0.694	0.775	1.12	6.744	8.548	0.3426	0.3973	2.310	3.396	
Soya	10.4	0.689	0.772	1.12	3.805	4.409	0.1235	0.1372	0.4699	0.6049	
	10.4	0.725	0.757	1.04	3.529	4.255	0.1215	0.1257	0.4288	0.5349	1 MHz Data
	11.4	0.712	0.762	1.07	4.428	5.180	0.1710	0.1883	0.7572	0.9780	
	11.4	0.720	0.765	1.06	4.573	5.316	0.1777	0.1946	0.8126	1.034	Samples from
	13.1	0.702	0.754	1.07	4.652	5.602	0.1902	0.2101	0.8849	1.177	various parts
	13.9	0.699	0.765	1.09	5.854	6.986	0.2284	0.2508	1.337	1.752	of U.S.A.
	14.5	0.723	0.757	1.05	5.571	6.540	0.2112	0.2304	1.177	1.507	
	14.8	0.697	0.748	1.07	5.993	7.240	0.2514	0.2757	1.507	1.996	
	16.1	0.682	0.720	1.06	6.591	7.945	0.2629	0.2748	1.733	2.183	
	16.9	0.670	0.723	1.08	7.181	8.852	0.2535	0.2755	1.820	2.439	

GRAIN	Percent Moisture	DENSITY grams/cubic cm. Dropped	DENSITY grams/cubic cm. Settled	Density Ratio Settled to Dropped	ϵ' Dropped	ϵ' Settled	tan δ Dropped	tan δ Settled	ϵ'' Dropped	ϵ'' Settled	Remarks
Corn	17.7	0.661	0.715	1.08	4.975	5.680	0.1270	0.1409	0.6318	0.8004	
	23.3	0.611	0.682	1.12	5.265	6.702	0.2925	0.3211	1.5401	2.152	5 MHz Data
	26.0	0.637	0.680	1.07	6.097	6.922	0.3028	0.3139	1.8461	2.173	Samples from various
	29.0	0.520	0.577	1.11	5.723	6.724	0.5202	0.5448	2.978	3.663	parts of U.S.A.
	30.9	0.512	0.565	1.10	6.129	6.937	0.5598	0.5874	3.431	4.075	11/1/76
	34.0	0.509	0.565	1.11	7.072	8.426	0.8511	0.8106	6.019	6.830	
Corn	8.5	0.611	0.635	1.04	2.928	3.073	0.1439	0.1577	0.4213	0.4846	
	10.4	0.606	0.640	1.06	3.146	3.358	0.0869	0.0876	0.2734	0.2942	
	12.9	0.619	0.646	1.04	3.516	3.826	0.0837	0.0934	0.2493	0.3573	5 MHz Data
	15.8	0.617	0.655	1.06	3.969	4.335	0.1220	0.1263	0.4842	0.5475	of 12/15/76
	19.1	0.589	0.637	1.08	4.396	5.050	0.1870	0.2046	0.8221	1.033	All samples from
	22.4	0.559	0.619	1.11	4.827	5.546	0.2797	0.3043	1.350	1.688	same field. Air dried
	25.7	0.538	0.591	1.10	4.920	6.013	0.3604	0.3949	1.773	2.375	on cob from 39%
	28.6	0.509	0.584	1.15	5.456	6.424	0.5031	0.5341	2.745	3.431	down to 8.5%.
	30.9	0.521	0.562	1.08	5.900	7.209	0.6282	0.6972	3.706	5.026	
	33.7	0.497	0.560	1.13	6.331	7.916	0.7605	0.8536	4.815	6.758	
	39.0	0.506	0.565	1.12	6.624	7.951	0.8599	0.8186	5.696	6.509	

GRAIN	Percent Moisture	DENSITY grams/cubic cm. Dropped	Settled	Density Ratio Settled to Dropped	ϵ' Dropped	Settled	$\tan\delta$ Dropped	Settled	ϵ'' Dropped	Settled	Remarks
Wheat	10.7										
	13.4										Wheat data not measured at 5 MHz.
	14.3										
	16.0										
	16.6										
	18.4										
	18.5										
	21.2										
	10.4	0.707	0.751	1.06	3.483	3.866	0.1087	0.1197	0.3785	0.4628	
Soya	10.4	0.720	0.757	1.05	3.458	3.816	0.1003	0.1074	0.3468	0.4100	5 MHz Data
	11.4	0.710	0.748	1.05	3.870	4.276	0.1496	0.1650	0.5790	0.7055	of 12/15/76
	11.4	0.715	0.757	1.06	4.002	4.505	0.0312	0.1871	0.1247	0.8427	Samples from
	13.1	0.702	0.748	1.07	4.079	4.641	0.1523	0.1702	0.6211	0.7898	various parts
	13.9	0.697	0.748	1.07	4.668	5.377	0.1782	0.1939	0.8320	1.043	of U.S.A.
	14.5	0.720	0.754	1.05	4.594	5.267	0.1765	0.1940	0.8109	1.022	
	14.8	0.673	0.734	1.09	4.713	5.449	0.1945	0.2146	0.9165	1.170	
	16.1	0.680	0.728	1.07	5.036	5.837	0.2092	0.2293	1.054	1.338	
	16.9	0.673	0.720	1.07	5.468	6.422	0.2332	0.2511	1.275	1.612	
Soya	10.4	0.710	0.765	1.08	3.406	3.858	0.1018	0.1117	0.3468	0.4311	5 MHz Data
	11.4	0.723	0.760	1.05	3.791	4.372	0.1388	0.1517	0.5262	0.6632	of 1/19/77
	11.4	0.717	0.769	1.07	3.911	4.469	0.1507	0.1649	0.5895	0.7371	Repeat measurements on above samples

		DENSITY grams/cubic cm.			ϵ'		$\tan\delta$		ϵ''		
GRAIN	Percent Moisture	Dropped	Settled	Density Ratio Settled to Dropped	Dropped	Settled	Dropped	Settled	Dropped	Settled	Remarks
Corn	17.7	0.661	0.723	1.09	4.842	5.371	0.1165	0.1256	0.5641	0.6746	10 MHz Data
	23.3	0.607	0.675	1.11	5.028	6.283	0.2192	0.2475	1.102	1.555	of 11/1/76
	26.0	0.629	0.680	1.08	5.471	6.345	0.2303	0.2492	1.260	1.581	Samples from
	29.0	0.530	0.575	1.08	5.077	6.145	0.3969	0.4205	2.015	2.584	various parts
	30.9	0.509	0.559	1.10	5.466	6.325	0.4101	0.4360	2.241	2.758	of U.S.A
	34.0	0.502	0.573	1.14	5.788	7.203	0.5384	0.6059	3.116	4.364	
Corn	8.5	0.615	0.625	1.02	2.699	2.870	0.0724	0.0754	0.1954	0.2164	10 MHz Data
	10.4	0.629	0.633	1.01	2.962	3.178	0.0784	0.0781	0.2322	0.2482	All samples from
	12.9	0.623	0.664	1.07	3.362	3.616	0.0738	0.0729	0.2481	0.2636	same field. Air
	15.8	0.606	0.652	1.08	3.699	4.063	0.0827	0.0908	0.3059	0.3689	dried on cob from
	19.1	0.586	0.637	1.09	4.091	4.758	0.1367	0.1463	0.5591	0.6960	39% to 8.5 %
	22.4	0.547	0.615	1.12	4.283	5.161	0.2020	0.2238	0.8651	1.155	
	25.7	0.531	0.596	1.12	4.675	5.553	0.2708	0.2934	1.266	1.629	12/15/76
	28.6	0.514	0.586	1.14	4.879	5.823	0.3535	0.3731	1.725	2.172	
	30.9	0.505	0.579	1.15	5.170	6.302	0.4336	0.4451	2.242	2.805	
	33.7	0.514	0.582	1.13	5.723	7.089	0.5612	0.5554	3.212	3.938	
	39.0	0.504	0.567	1.12	7.194	9.621	0.8628	1.007	6.207	9.688	

GRAIN	Percent Moisture	DENSITY grams/cubic cm. Dropped	Settled	Density Ratio Settled to Dropped	ϵ' Dropped	ϵ' Settled	$\tan\delta$ Dropped	$\tan\delta$ Settled	ϵ'' Dropped	ϵ'' Settled	Remarks
Wheat	10.7	0.826	0.883	1.07	3.915	4.347	0.0756	0.0808	0.2958	0.3514	10 MHz Data
	13.4	0.811	0.862	1.06	4.442	4.920	0.0864	0.0921	0.3839	0.4533	of 11/4/76
	14.3	0.803	0.848	1.06	4.485	4.974	0.0752	0.0808	0.3373	0.4021	Samples from
	16.0	0.779	0.829	1.06	4.615	5.294	0.0882	0.0970	0.4070	0.5135	western Kansas
	16.6	0.715	0.791	1.11	4.402	4.976	0.0872	0.0958	0.3839	0.4765	and various other
	18.4	0.746	0.819	1.10	5.031	5.762	0.1252	0.1342	0.6299	0.7735	parts of U.S.A.
	18.5	0.746	0.796	1.07	4.863	5.566	0.1114	0.1222	0.5417	0.6807	
	21.2	0.692	0.759	1.10	5.119	5.927	0.1775	0.1697	0.9887	1.006	
Soya	10.4	0.710	0.748	1.05	3.598	4.067	0.1452	0.1505	0.5224	0.6119	10 MHz Data
	10.4	0.720	0.751	1.04	3.301	3.603	0.0815	0.0849	0.2689	0.3057	of 12/13/76
	11.4	0.707	0.742	1.05	4.067	4.614	0.1751	0.2046	0.7122	0.9441	Samples from
	11.4	0.725	0.765	1.06	4.168	4.680	0.1873	0.2051	0.7808	0.9599	Various parts
	13.1	0.699	0.736	1.05	3.834	4.367	0.1251	0.1412	0.4797	0.6166	of U.S.A.
	13.9	0.702	0.748	1.07	4.404	4.998	0.1676	0.1940	0.7379	0.9696	
	14.5	0.710	0.751	1.06	4.212	4.880	0.1502	0.1663	0.6325	0.8115	
	14.8	0.680	0.731	1.08	4.347	5.012	0.1710	0.1903	0.7432	0.9538	
	16.1	0.678	0.723	1.07	4.070	5.372	0.1878	0.2109	0.7645	1.133	
	16.9	0.680	0.707	1.04	4.916	5.684	0.2123	0.2308	1.043	1.312	
Soya	10.4	0.717	0.754	1.05	3.314	3.685	0.0999	0.1001	0.3111	0.3690	10 MHz Data
	11.4	0.723	0.765	1.06	3.656	4.086	0.1226	0.1316	0.4481	0.5376	of 1/19/77 Repeat
	11.4	0.720	0.762	1.06	3.728	4.210	0.1344	0.1477	0.5009	0.6220	measurements on above samples.

GRAIN	Percent Moisture	DENSITY grams/cubic cm. Dropped	DENSITY grams/cubic cm. Settled	Density Ratio Settled to Dropped	ϵ' Dropped	ϵ' Settled	$\tan\delta$ Dropped	$\tan\delta$ Settled	ϵ'' Dropped	ϵ'' Settled	Remarks
Corn	17.7	0.666	0.723	1.09	4.513	5.065	0.0957	0.1036	0.4319	0.5247	30 MHz Data
	23.3	0.606	0.677	1.12	4.524	5.555	0.1497	0.1660	0.6772	0.9221	of 11/1/76
	26.0	0.640	0.677	1.06	5.158	6.056	0.1585	0.1692	0.8175	1.025	Samples from
	29.0	0.512	0.587	1.15	4.310	5.419	0.2228	0.2533	0.9602	1.373	various parts
	30.9	0.502	0.573	1.14	4.930	5.797	0.2486	0.2544	1.226	1.475	of U.S.A.
	34.0	0.514	0.570	1.11	4.975	6.095	0.4218	0.3432	2.098	2.092	
	26.0				4.887	5.579	0.1465	0.1569	0.7160	0.8753	Repeated measure-
	29.0				4.443	5.286	0.2313	0.2575	1.028	1.361	ments of above (3)
	30.9				4.778	5.536	0.2403	0.2538	1.148	1.405	samples
	34.0				5.097	5.863	0.3566	0.3681	1.818	2.158	
Corn	8.5	0.608	0.640	1.05	2.587	2.710	0.0743	0.0774	0.1922	0.2098	
	10.4	0.619	0.648	1.05	2.822	3.022	0.0712	0.0768	0.2009	0.2321	30 MHz Data
	12.9	0.619	0.639	1.03	3.191	3.412	0.0738	0.0781	0.2355	0.2665	of 12/15/76
	15.8	0.606	0.654	1.08	3.548	3.870	0.0820	0.0877	0.2909	0.3394	All samples from
	19.1	0.576	0.642	1.11	3.762	4.410	0.1013	0.1122	0.3811	0.4949	same field. Air
	22.4	0.557	0.619	1.11	3.948	4.641	0.1361	0.1496	0.5373	0.6940	dried on cob from
	25.7	0.532	0.602	1.13	4.160	4.952	0.1725	0.1904	0.7176	0.9430	39% to 8.5%
	28.6	0.512	0.579	1.13	4.219	5.160	0.2108	0.2390	0.8894	1.233	
	30.9	0.516	0.568	1.10	4.696	5.500	0.2804	0.3061	1.302	1.684	
	33.7	0.502	0.555	1.11	4.789	5.566	0.3400	0.5300	1.628	2.950	
	39.0	0.498	0.565	1.13	5.741	7.296	0.4660	0.5401	2.661	3.940	

GRAIN	Percent Moisture	DENSITY grams/cubic cm. Dropped	DENSITY grams/cubic cm. Settled	Density Ratio Settled to Dropped	ϵ' Dropped	ϵ' Settled	$\tan\delta$ Dropped	$\tan\delta$ Settled	ϵ'' Dropped	ϵ'' Settled	Remarks
Wheat	10.7	0.829	0.892	1.08	3.689	4.096	0.0912	0.0984	0.3363	0.4030	30 MHz Data.
	13.4	0.803	0.854	1.06	4.053	4.495	0.0904	0.0970	0.3664	0.4361	of 11/4/76
	14.3	0.808	0.854	1.06	4.151	4.594	0.0864	0.0939	0.3586	0.4313	Samples from
	16.0	0.772	0.832	1.08	4.401	5.023	0.0877	0.0970	0.3858	0.4870	western Kansas
	16.6	0.719	0.791	1.10	4.208	4.760	0.0899	0.0976	0.3784	0.4646	and various other
	18.4	0.754	0.821	1.09	4.692	5.386	0.0951	0.1081	0.4464	0.5823	parts of U.S.A.
	18.5	0.743	0.796	1.07	4.573	5.118	0.0950	0.1038	0.4344	0.5310	
	21.2	0.686	0.765	1.12	4.786	5.666	0.1181	0.1333	0.5653	0.7551	
Soya ·	10.4	0.704	0.751	1.07	3.115	3.503	0.0805	0.0884	0.2509	0.3097	30 MHz Data
	10.4	0.723	0.754	1.04	3.112	3.447	0.0778	0.0863	0.2422	0.2976	of 12/15/76
·	11.4	0.720	0.746	1.03	3.437	3.776	0.1033	0.1123	0.3550	0.4241	samples from
·	11.4	0.723	0.769	1.06	3.464	3.772	0.1040	0.1032	0.3602	0.3894	various parts
	13.1	0.697	0.742	1.06	3.593	3.975	0.1157	0.1250	0.4157	0.4968	of U.S.A.
	13.9	0.710	0.745	1.05	4.032	4.472	0.1473	0.1586	0.5939	0.7092	
	14.5	0.707	0.745	1.05	3.876	4.360	0.1327	0.1472	0.5143	0.6419	
	14.8	0.680	0.717	1.05	4.001	4.599	0.1424	0.1571	0.5696	0.7160	
	16.1	0.675	0.717	1.06	4.166	4.836	0.1604	0.1769	0.6683	0.8557	
	16.9	0.675	0.710	1.05	4.416	5.155	0.1752	0.1954	0.7735	1.007	
Soya ·	10.4	0.712	0.765	1.07	3.099	3.495	0.0832	0.0936	0.2579	0.3271	30 MHz Data
·	11.4	0.725	0.765	1.06	3.346	3.756	0.1020	0.1120	0.3412	0.4207	of 1/19/77 Repeat
·	11.4	0.723	0.769	1.06	3.389	3.849	0.1053	0.1147	0.3567	0.4414	measurements on above samples

GRAIN	Percent Moisture	DENSITY grams/cubic cm. Dropped	Settled	Density Ratio Settled to Dropped	ϵ' Dropped	Settled	$\tan\delta$ Dropped	Settled	ϵ'' Dropped	Settled	Remarks
Corn	17.7	0.664	0.712	1.07	4.391	4.765	0.0948	0.0985	0.4163	0.4694	50 MHz Data.
	23.3	0.604	0.677	1.12	4.442	5.169	0.1334	0.1434	0.5926	0.7412	of 11/1/76
	26.0	0.642	0.694	1.08	4.618	5.444	0.1273	0.1390	0.5879	0.7567	Samples from
	29.0	0.516	0.557	1.08	4.115	4.867	0.1849	0.2019	0.7609	0.9826	various parts
	30.9	0.500	0.573	1.15	4.566	5.298	0.1902	0.2027	0.8684	1.074	of U.S.A.
	34.0	0.506	0.565	1.12	4.689	5.630	0.2822	0.2972	1.323	1.673	
Corn	8.5	0.608	0.631	1.04	2.506	2.640	0.0710	0.0743	0.1779	0.1962	50 MHz Data
	10.4	0.615	0.642	1.04	2.753	2.948	0.0764	0.0821	0.2103	0.2420	of 12/15/76
	12.9	0.623	0.635	1.02	3.077	3.306	0.0785	0.0872	0.2415	0.2883	All samples from
	15.8	0.602	0.640	1.06	3.481	3.807	0.0833	0.0893	0.2900	0.3400	same field. Air
	19.1	0.591	0.633	1.07	3.754	4.281	0.0963	0.1043	0.3616	0.4463	dried on cob from
	22.4	0.554	0.625	1.13	3.917	4.541	0.1179	0.1282	0.4619	0.5821	39% to 8.5%
	25.7	0.537	0.604	1.12	4.085	4.783	0.1447	0.1565	0.5913	0.7487	
	28.6	0.524	0.577	1.10	4.025	4.927	0.1738	0.1962	0.6993	0.9668	
	30.9	0.505	0.572	1.13	4.389	5.386	0.2161	0.2404	0.9487	1.295	
	33.7	0.496	0.568	1.15	4.337	5.351	0.2684	0.2853	1.164	1.527	
	39.0	0.508	0.573	1.13	5.471	6.632	0.3637	0.4781	1.990	3.171	

GRAIN	Percent Moisture	DENSITY grams/cubic cm. Dropped	DENSITY grams/cubic cm. Settled	Density Ratio Settled to Dropped	ϵ' Dropped	ϵ' Settled	$\tan\delta$ Dropped	$\tan\delta$ Settled	ϵ'' Dropped	ϵ'' Settled	Remarks
Wheat	10.7	0.829	0.885	1.07	3.555	3.931	0.0971	0.1053	0.3454	0.4139	50 MHz Data
	13.4										of 11/4/76
	14.3	0.782	0.837	1.07	4.053	4.336	0.0901	0.0959	0.3652	0.4159	Samples from
	16.0										western Kansas
	16.6	0.723	0.791	1.09	4.050	4.598	0.0933	0.1018	0.3778	0.4682	and various other
	18.4										parts of U.S.A.
	18.5	0.739	0.779	1.05	4.479	4.773	0.0937	0.0994	0.4198	0.4745	
	21.2										
Soya	10.4	0.720	0.757	1.05	3.079	3.452	0.0817	0.0909	0.2514	0.3139	50 MHz Data
	10.4	0.725	0.760	1.05	3.055	3.328	0.0783	0.0837	0.2392	0.2785	of 12/15/76
	11.4	0.725	0.754	1.04	3.353	3.648	0.1031	0.1102	0.3457	0.4019	Samples from
	11.4	0.723	0.778	1.08	3.338	3.777	0.1033	0.1144	0.3448	0.4320	various parts
	13.1	0.702	0.723	1.03	3.454	3.843	0.1100	0.1184	0.3801	0.4552	of U.S.A.
	13.9	0.707	0.748	1.06	3.827	4.349	0.1373	0.1517	0.5253	0.6598	
	14.5	0.717	0.757	1.06	3.724	4.250	0.1248	0.1373	0.4647	0.5833	
	14.8	0.682	0.715	1.05	3.862	4.345	0.1352	0.1474	0.5221	0.6406	
	16.1	0.673	0.725	1.08	3.976	4.593	0.1519	0.1658	0.6039	0.7615	
	16.9	0.670	0.725	1.08	4.290	4.940	0.1683	0.1851	0.7218	0.9145	

		DENSITY grams/cubic cm.			ϵ'		$\tan\delta$		ϵ''		Remarks
GRAIN	Percent Moisture	Dropped	Settled	Density Ratio Settled to Dropped	Dropped	Settled	Dropped	Settled	Dropped	Settled	
Corn	17.7	0.673	0.710	1.05	4.214	4.699	0.0992	0.1057	0.4180	0.4967	100 MHz Data
	23.3	0.607	0.675	1.11	4.263	4.971	0.1158	0.1227	0.4937	0.6100	of 11/1/76
	26.0	0.644	0.702	1.09	4.526	5.293	0.1141	0.1232	0.5164	0.6520	Samples from
	29.0	0.534	0.589	1.10	3.868	4.687	0.1385	0.1545	0.5357	0.7242	various parts
	30.9	0.513	0.584	1.14	4.357	5.264	0.1537	0.1678	0.6697	0.8833	of U.S.A.
	34.0	0.509	0.577	1.13	4.447	5.149	0.1957	0.2093	0.8703	1.078	
Corn	8.5	0.615	0.640	1.04	2.450	2.554	0.0749	0.0777	0.1835	0.1984	100 MHz Data
	10.4	0.606	0.640	1.06	2.729	2.892	0.0828	0.0884	0.2260	0.2557	of 12/15/76
	12.9	0.613	0.644	1.05	2.995	3.196	0.0890	0.0937	0.2666	0.2995	All samples from
	15.8	0.602	0.655	1.08	3.382	3.683	0.0911	0.0969	0.3081	0.3569	same field. Air
	19.1	0.591	0.644	1.09	3.754	4.203	0.0965	0.1057	0.3621	0.4443	dried on cob from
	22.4	0.554	0.619	1.12	3.759	4.405	0.1075	0.1147	0.4042	0.5052	39% to 8.5%
	25.7	0.538	0.598	1.11	3.739	4.327	0.1156	0.1276	0.4322	0.5524	
	28.6	0.512	0.578	1.13	3.929	4.488	0.1405	0.1513	0.5521	0.6990	
	30.9	0.510	0.578	1.13	4.072	4.805	0.1605	0.1782	0.6537	0.8561	
	33.7	0.496	0.559	1.13	4.227	5.194	0.1979	0.2245	0.8365	1.166	
	39.0	0.502	0.572	1.14	5.066	5.984	0.2907	0.3120	1.473	1.867	

GRAIN	Percent Moisture	DENSITY grams/cubic cm. Dropped	DENSITY grams/cubic cm. Settled	Density Ratio Settled to Dropped	ε' Dropped	ε' Settled	tan δ Dropped	tan δ Settled	ε" Dropped	ε" Settled	Remarks
Wheat	10.7	0.829	0.889	1.07	3.419	3.764	0.1056	0.1139	0.3610	0.4288	100 MHz Data
	13.4	0.808	0.871	1.08	3.797	4.208	0.1053	0.1147	0.3998	0.4827	of 11/4/76
	14.3	0.798	0.840	1.05	3.913	4.146	0.1039	0.1079	0.4064	0.4474	Samples from
	16.0	0.772	0.832	1.08	4.106	4.656	0.1023	0.1125	0.4201	0.5239	western Kansas
	16.6	0.721	0.782	1.08	3.875	4.370	0.1006	0.1094	0.3897	0.4782	and various other
	18.4	0.743	0.814	1.10	4.429	4.975	0.1049	0.1132	0.4644	0.5632	parts of U.S.A.
	18.5	0.719	0.768	1.07	4.164	4.524	0.0982	0.1048	0.4087	0.4742	
	21.2	0.686	0.756	1.10	4.494	5.105	0.1107	0.1205	0.4973	0.6153	
Soya	10.4	0.715	0.748	1.05	2.957	3.289	0.0835	0.0923	0.2468	0.3037	100 MHz Data
	10.4	0.720	0.751	1.04	2.947	3.222	0.0823	0.0895	0.2427	0.2883	of 12/15/76
	11.4	0.720	0.751	1.04	3.191	3.537	0.1037	0.1116	0.3309	0.3948	Samples from
	11.4	0.720	0.754	1.05	3.235	3.596	0.1037	0.1136	0.3354	0.4086	various parts
	13.1	0.697	0.734	1.05	3.269	3.663	0.1085	0.1187	0.3548	0.4348	of U.S.A.
	13.9	0.702	0.734	1.05	3.625	4.031	0.1329	0.1440	0.4820	0.5805	
	14.5	0.710	0.757	1.07	3.554	4.021	0.1236	0.1353	0.4390	0.5440	
	14.8	0.675	0.728	1.08	3.640	4.111	0.1291	0.1406	0.4700	0.5780	
	16.1	0.668	0.717	1.07	3.786	4.247	0.1434	0.1545	0.5429	0.6561	
	16.9	0.673	0.731	1.09	3.966	4.597	0.1539	0.1707	0.6104	0.7846	

GRAIN	Percent Moisture	DENSITY grams/cubic cm. Dropped	DENSITY grams/cubic cm. Settled	Density Ratio Settled to Dropped	ε′ Dropped	ε′ Settled	tan δ Dropped	tan δ Settled	ε″ Dropped	ε″ Settled	Remarks
Corn	17.7	0.682	0.734	1.08	4.177	4.609	0.1079	0.1142	0.4507	0.5263	150 MHz Data of 11/1/76 Samples from various parts of U.S.A.
	23.3	0.607	0.680	1.12	4.119	4.970	0.1100	0.1226	0.4530	0.6093	
	26.0	0.644	0.689	1.07	4.339	5.261	0.0689	0.0895	0.2989	0.4709	
	29.0	0.524	0.582	1.11	3.931	4.691	0.0877	0.1062	0.2571	0.4971	
	30.9	0.520	0.568	1.09	4.279	5.047	0.1079	0.1267	0.4617	0.6395	
	34.0	0.516	0.562	1.09	4.226	5.026	0.1325	0.1539	0.5599	0.7735	
Corn	8.5										150 MHz Data of 12/15/76 All samples from same field. Air dried on cob from 39% to 8.5%
	10.4	0.621	0.646	1.04	2.637	2.772	0.0860	0.0916	0.2268	0.2539	
	12.9	0.625	0.655	1.05	2.965	3.141	0.0979	0.1021	0.2903	0.3207	
	15.8										
	19.1										
	22.4										
	25.7										
	28.6	0.518	0.577	1.11	3.838	4.502	0.1177	0.1383	0.4519	0.6228	
	30.9	0.513	0.565	1.10	3.941	4.777	0.1380	0.1557	0.5437	0.7439	
	33.7	0.505	0.562	1.11	4.042	4.908	0.1596	0.1774	0.6450	0.8804	
	39.0	0.502	0.570	1.14	4.837	5.994	0.2222	0.2400	1.075	1.438	
Corn	23.3	0.611	0.664	1.09	4.012	4.895	0.1072	0.1218	0.4302	0.5963	150 MHz Data Repeated measurements on above samples from various parts of U.S.A.
	26.0	0.623	0.685	1.10	4.427	5.205	0.1078	0.1177	0.4772	0.6126	
	29.0	0.520	0.582	1.12	3.904	4.595	0.1254	0.1346	0.4896	0.6184	
	30.9	0.506	0.573	1.13	4.180	4.996	0.1320	0.1449	0.5517	0.7239	
	34.0	0.497	0.565	1.14	4.362	5.122	0.1746	0.1853	0.7617	0.9494	
Corn	10.4	0.615	0.648	1.05	2.556	2.735	0.0844	0.0913	0.2157	0.2497	150 MHz Data Repeated measurements on samples from same field listed above.
	12.9	0.621	0.657	1.06	2.887	3.110	0.0924	0.0996	0.2668	0.3098	

GRAIN	Percent Moisture	DENSITY grams/cubic cm. Dropped	DENSITY grams/cubic cm. Settled	Density Ratio Settled to Dropped	ϵ' Dropped	ϵ' Settled	$\tan\delta$ Dropped	$\tan\delta$ Settled	ϵ'' Dropped	ϵ'' Settled	Remarks
Wheat	10.7										
	13.4										Wheat not measured at 150 MHz
	14.3										
	16.0										
	16.6										
	18.4										
	18.5										
	21.2										
Soya	10.4	0.720	0.760	1.06	2.923	3.213	0.0844	0.0922	0.2467	0.2960	150 MHz Data of 12/15/76 Samples from various parts of U.S.A.
	10.4	0.723	0.757	1.05	2.886	3.120	0.0682	0.0753	0.1969	0.2349	
	11.4	0.717	0.751	1.05	3.118	3.457	0.1012	0.1103	0.3157	0.3814	
	11.4	0.717	0.762	1.06	3.139	3.485	0.1010	0.1104	0.3172	0.3847	
	13.1	0.702	0.734	1.05	3.176	3.539	0.0938	0.1051	0.2979	0.3719	
	13.9	0.697	0.748	1.07	3.494	3.920	0.1196	0.1323	0.4179	0.5186	
	14.5	0.715	0.762	1.07	3.443	3.857	0.1084	0.1218	0.3731	0.4699	
	14.8	0.682	0.728	1.07	3.498	3.963	0.1145	0.1282	0.4004	0.5079	
	16.1	0.680	0.712	1.05	3.654	4.078	0.1270	0.1406	0.4640	0.5736	
	16.9	0.670	0.717	1.07	3.854	4.359	0.1386	0.1497	0.5340	0.6526	

GRAIN	Percent Moisture	DENSITY grams/cubic cm. Dropped	Settled	Density Ratio Settled to Dropped	ϵ' Dropped	Settled	tan δ Dropped	Settled	ϵ'' Dropped	Settled	Remarks
Corn	17.7	0.664	0.704	1.06	4.016	4.463	0.1125	0.1196	0.4519	0.5338	200 MHz Data
	23.3	0.613	0.675	1.10	4.009	4.903	0.1102	0.1220	0.4418	0.5981	of 11/1/76
	26.0	0.633	0.689	1.09	4.387	5.150	0.1080	0.1195	0.4738	0.6154	Samples from
	29.0	0.518	0.582	1.12	3.628	4.698	0.1234	0.1283	0.4477	0.6027	various parts
	30.9	0.509	0.593	1.17	4.222	4.993	0.1250	0.1378	0.5278	0.6881	of U.S.A.
	34.0	0.507	0.577	1.14	4.269	5.135	0.1548	0.1702	0.6608	0.8740	
Corn	8.5	0.608	0.651	1.07	2.351	2.468	0.0742	0.0779	0.1744	0.1923	200 MHz Data
	10.4	0.619	0.642	1.04	2.539	2.697	0.0861	0.0918	0.2186	0.2476	of 12/15/76
	12.9	0.619	0.657	1.06	2.896	3.059	0.0963	0.1009	0.2789	0.3087	All samples from
	15.8	0.621	0.648	1.04	3.222	3.466	0.1000	0.1055	0.3222	0.3657	same field. Air
	19.1	0.587	0.642	1.09	3.500	3.994	0.1036	0.1132	0.3625	0.4522	dried on cob from
	22.4	0.562	0.600	1.07	3.646	4.171	0.1067	0.1143	0.3889	0.4768	39% to 8.5%
	25.7	0.536	0.604	1.13	3.653	4.359	0.1106	0.1215	0.4039	0.5296	
	28.6	0.517	0.584	1.13	3.795	4.446	0.1196	0.1282	0.4539	0.5698	
	30.9	0.502	0.570	1.14	4.005	4.702	0.1309	0.1424	0.5241	0.6696	
	33.7	0.504	0.557	1.11	4.223	4.937	0.1503	0.1680	0.6346	0.8292	
	39.0	0.504	0.568	1.13	4.721	5.923	0.2044	0.2331	0.9649	1.381	

GRAIN	Percent Moisture	DENSITY grams/cubic cm. Dropped	DENSITY grams/cubic cm. Settled	Density Ratio Settled to Dropped	ε′ Dropped	ε′ Settled	tan δ Dropped	tan δ Settled	ε″ Dropped	ε″ Settled	Remarks
Wheat	10.7	0.826	0.895	1.08	3.324	3.633	0.1082	0.1164	0.3597	0.4231	200 MHz Data
	13.4	0.811	0.871	1.07	3.574	3.985	0.1162	0.1256	0.4153	0.5004	of 11/4/76
	14.3	0.801	0.829	1.03	3.746	3.994	0.1166	0.1222	0.4367	0.4881	Samples from
	16.0	0.779	0.834	1.07	3.977	4.462	0.1144	0.1246	0.4549	0.5560	western Kansas
	16.6	0.723	0.789	1.09	3.794	4.310	0.0829	0.1214	0.3143	0.5234	and various other
	18.4	0.745	0.821	1.10	4.115	4.771	0.1112	0.1229	0.4576	0.5864	parts of U.S.A.
	18.5	0.723	0.772	1.07	3.992	4.401	0.1122	0.1159	0.4479	0.5102	
	21.2	0.692	0.757	1.09	4.383	5.081	0.1120	0.1232	0.4907	0.6261	
Soya	10.4	0.717	0.751	1.05	2.857	3.179	0.0847	0.0933	0.2420	0.2964	200 MHz Data
	10.4	0.731	0.765	1.05	2.872	3.112	0.0834	0.0897	0.2396	0.2790	of 12/15/76
	11.4	0.715	0.751	1.05	3.077	3.356	0.1022	0.1100	0.3146	0.3692	Samples from
	11.4	0.728	0.757	1.04	3.095	3.423	0.1038	0.1129	0.3213	0.3867	various parts
	13.1	0.697	0.751	1.08	3.143	3.533	0.1076	0.1182	0.3381	0.4174	of U.S.A.
	13.9	0.707	0.736	1.04	3.511	3.856	0.1296	0.1396	0.4550	0.5382	
	14.5	0.710	0.748	1.05	3.420	3.837	0.1223	0.1329	0.4182	0.5100	
	14.8	0.680	0.723	1.06	3.482	3.940	0.1433	0.1483	0.4989	0.5845	
	16.1	0.682	0.717	1.05	3.648	4.072	0.1364	0.1532	0.4976	0.6236	
	16.9	0.675	0.725	1.07	3.806	4.320	0.1458	0.0898	0.5548	0.5151	

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A set of coaxial sample holders together with a measurement and data reduction technique has been developed and applied to the study of the dielectric properties ($\varepsilon^*=\varepsilon'-j\varepsilon''$) of wheat, corn, and soya over the 1 to 200 MHz range. Particular attention was given to the behavior of the dielectric properties as a function of percent moisture content, frequency, and packing density. Data were also taken to evaluate the dependence of dielectric properties on temperature and sample holder configuration. Some study was also devoted to the correlation between dielectric constant (ε'), loss factor (ε''), loss tangent ($\varepsilon''/\varepsilon'$), and percent moisture content. Particular emphasis was devoted to a study of high moisture corn (up to 40%).

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Dielectric properties; grain; loss tangent; moisture.

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